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FLOW CONTROL
for
UNSTEADY AND SEPARATED FLOWS
and
TURBULENT MIXING

ANNUAL REPORT
October 1, 1987 - September 30, 1988

Research Supported by the
Air Force Office of Scientific Research
DOD URI Program
Contract AF F49620-86-K-0020

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STANFORD UNIVERSITY

October 31, 1988

AD-A205 989

AFOSR-TR-89-0232
Chief, Technical Information Division
AFOSR-TR-89-0232
AFOSR-TR-89-0232
AFOSR-TR-89-0232

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

1a REPORT SECURITY CLASSIFICATION Unclassified			1b RESTRICTIVE MARKINGS		
2a SECURITY CLASSIFICATION AUTHORITY			3. DISTRIBUTION / AVAILABILITY OF REPORT Approved for public release. Distribution is unlimited.		
2b. DECLASSIFICATION / DOWNGRADING SCHEDULE					
4. PERFORMING ORGANIZATION REPORT NUMBER(S)			5. MONITORING ORGANIZATION REPORT NUMBER(S) AFOSR-TR-89-0232		
6a. NAME OF PERFORMING ORGANIZATION Stanford University		6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION AFOSR		
6c. ADDRESS (City, State, and ZIP Code) Stanford, CA 94305			7b. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling Air Force Base, DC 20332-6448		
8a. NAME OF FUNDING / SPONSORING ORGANIZATION AFOSR/NA		8b. OFFICE SYMBOL (If applicable) NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER F 4962-86-K0020		
8c. ADDRESS (City, State, and ZIP Code) Bldg. 410 Bolling Air Force Base, DC 20332-6448			10. SOURCE OF FUNDING NUMBERS		
			PROGRAM ELEMENT NO 61103D	PROJECT NO 3484	TASK NO A1
11. TITLE (Include Security Classification) Flow Control for Unsteady and Separated Flows and Turbulent Mixing					
12. PERSONAL AUTHOR(S) W. C. Reynolds, J. K. Eaton, J. P. Johnston, L. Hesselink, D. J. Powell, L. Roberts, E. Kroo					
13a. TYPE OF REPORT Annual		13b. TIME COVERED FROM: 10/1/87 TO 9/30/88		14. DATE OF REPORT (Year, Month, Day) 1988, Oct 31	
15. PAGE COUNT 48					
16. SUPPLEMENTARY NOTATION:					
17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number) Flow control; turbulent mixing; unsteady boundary layers; separated flow; delta wings. (68) -		
FIELD	GROUP	SUB-GROUP			
19. ABSTRACT (Continue on reverse if necessary and identify by block number) A coordinated set of experimental research projects on flow control is being conducted by a team with experience in fluid mechanics and automatic control. The primary objective of this work is to develop new ways to control flows of technical interest and a generic approach to the design of flow control systems. Included are studies of mixing enhancement by excitation of jets, active control of unsteady turbulent boundary layers and separated flows, and active control of the vortical flow over delta wings using leading-edge blowing.					
20. DISTRIBUTION / AVAILABILITY OF ABSTRACT <input type="checkbox"/> UNCLASSIFIED/UNLIMITED <input checked="" type="checkbox"/> SAME AS RPT. <input type="checkbox"/> DTIC USERS			21. ABSTRACT SECURITY CLASSIFICATION Unclassified		
22a. NAME OF RESPONSIBLE INDIVIDUAL James M. McMichael			22b. TELEPHONE (Include Area Code) (202) 767-4936		22c. OFFICE SYMBOL AFOSR/NA

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

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1. PROGRAM OVERVIEW

1.1 Motivation and Objectives

The ability to control fluid flows offers many new opportunities. For example, there is now evidence that it will be possible to exercise the following flow control on flight vehicles:

- control the airflow over a wing to prevent stall and vortex breakdown at high angle of attack in a supermaneuver;
- stabilize turbulent boundary layer flow to keep it laminar and thereby reduce drag;
- suppress separation in transient flows to improve propulsion performance;
- enhance mixing in jet ejectors to obtain compact thrust augmentors.

Thus, there is considerable incentive to develop our national technical capability in the new field of *flow control*, and this program is designed to contribute to this development.

Some of types of flow control may be achieved by relatively simple passive methods involving no more than clever geometrical design. Others will require some controlled forcing that can be done in an open-loop manner. The more difficult flow control tasks will require some sort of active feedback control. The development of these control methods will require advances in understanding of the physics of flows (especially turbulence), new capability in modeling flows in ways that are suitable for control system development, new ways to sense flow states, and new ways to actuate the flows in the manner necessary to effect the control. Hence, there is a significant need for more research in flow control.

The general objective of the program is to make significant advances in the engineering science and technology of flow control. The research team consists of faculty members and graduate students in the closely-knit Departments of Aeronautics/Astronautics and Mechanical Engineering, who have joined together to apply their expertise in fluid mechanics, aeronautics, and automatic control in a coordinated effort to advance the field of flow control.

1.2 Program Structure and General Status

The program is organized into three primary tasks:

1. control of jet flows;
2. control of unsteady turbulent boundary layers;
3. control of vortical flow over delta wings.

The work under task 1 is an outgrowth of our discovery that the astute combination of two modes of acoustic excitation can dramatically alter the flow structure and entrainment rate in jets (*blooming jets*). There are currently two sub-tasks:

- a. control of mixing in shrouded jets;
- b. feedback control of jets.

This year in subtask a we showed that high-Reynolds number jets can be made to bloom in shrouds, producing a very significant increase in the entrained secondary flow. Present work is concentrating on new means to actuate this control in stronger jets, where loud-speakers are not sufficiently powerful. In subtask b we built an open-loop controller that can maintain a jet in a blooming state over a wide range of flow transients. We found that this flow can be controlled without feedback because the perturbed flow is inherently very stable. Since the thrust of subtask b is to develop techniques for cases where feedback is essential, we have added a weak conical diffuser to the nozzle; this makes the jet flow inherently unstable, and so feedback will be essential. This flow is being used as a basis for developing a general methodology for feedback flow control.

Work under task 2 is an outgrowth of our work on unsteady turbulent boundary layer separation and active separation control. There are currently four subtasks:

- a. active control of unsteady separating flows;
- b. vortex generator jets for boundary layer control;
- c. active control of unsteady boundary layers;
- d. holographic vorticity measurement.

Subtasks (a) and (b) are carried out in special air flow facilities, and subtasks (c) and (d) in water flows. Subtask (a) examines the control of two-dimensional periodic separation by modification of the spanwise vorticity in the separation zone; this year we have demonstrated that properly-phased oscillations of a spanwise control flap in the separated region can be used to make drastic modifications in the structure of the separated zone. Work in this subtask also examines boundary layer separation control with articulated wall-mounted half-delta streamwise vortex generators; this year the transient flow field behind an a suddenly activated generator was mapped out and an apparatus with a row of activated generators was constructed. Subtask (b) explores the use of pulsed jets through holes in the surface as an alternative for introduction of unsteady longitudinal control vortices; data gathered this year shows that this is a very promising approach. Subtask (c) has been examining the response of a turbulent boundary layer to the sudden imposition of an adverse pressure gradient, both with and without longitudinal control vortices produced by wall-mounted half-delta generators; this work is nearly completed. In the coming year we plan to begin using the facility to study active feedback control of near-wall flows by injection or suction through wall slots in response to changes in the sensed near-wall velocity field. Subtask (d) has developed a new optical (holographic) method for direct measurement of the vorticity vector in a liquid flow; we expect to adapt this technology for use in the unsteady water flow channel (subtask c).

Task 3 studies the use of tangential leading edge blowing to control the vortical flow over a delta wing. There are four subtasks to this effort:

- a. obtain basic understanding of the unsteady vortical flow and the its influence by tangential leading edge blowing;
- b. develop an aerodynamic model for use in control system design and simulations;
- c. develop a control system for the model delta wing;

- d. analyze the capabilities of an aircraft utilizing this type of control in typical supermaneuvers.

The work is being carried out in a low-speed wind tunnel at Stanford. The concept was demonstrated in the first year of this program on a half-delta model. Experiments this past year have concentrated on a new full-delta model, and have shown remarkable control of the flow field is possible with very modest blowing control. Unseparated flow can be maintained to angles of attack as high as 60° , and large rolling moments can be obtained by unsymmetrical blowing. A newly-installed advanced flow visualization system has provided new insight into the flow structure and the time scales required for flow adjustment to the onset and removal of blowing. The simulation model has reached a stage of development where it is providing a description of the flow structure that is nearly adequate for use in the control system design and system simulation. The basic approach to a control system for unsteady blowing has been laid out, and a first-generation unsteady blowing actuator has been constructed.

In summary, all three tasks are progressing very well, in spite of especially difficult funding circumstances thrust upon us this past year. The situation is vastly improved for year three, and so we expect this program to progress essentially as originally planned. More details on the progress and plans for each of the tasks and subtasks is provided in sections 2-6 below. Section 2 covers the work on jet control; sections 3,4,5, and 6 describe the research on unsteady boundary layer control; and section 7 reviews progress on the control of vortical flow over delta wings.

1.3 Funding Situation

As a result of Congressional action that placed a cap on URI funding in any state, this project, along with all other AFOSR projects in California, was hit with a 40% reduction in funds below that originally proposed and approved for the second year. In order to accommodate this drastic cut with minimal impact on the program, we decided to forego purchase of some of the planned equipment and to eliminate faculty salary charges. The university also provided other assistance so that we did not have to terminate any of the students or Research Associates employed by the program. The participating faculty themselves contributed by working on the project during the summer *without compensation*. Through these unusual actions we were able to meet almost all of our program objectives for the second year, in spite of this extremely adverse funding situation.

Neither Stanford nor the participating faculty were prepared to subsidize this program in a similar way this year. Fortunately the Congress removed this geographical cap on the URI program, at the same time making some reductions in the overall URI funding level. The AFOSR has chosen to distribute the overall reductions in the URI program evenly across the program. The net result for us will be a very modest reduction below the budget originally proposed and approved for the coming third year, and with modest university subsidies (in the form of partial reductions in faculty charges) we now expect to carry out the research program essentially as originally proposed.

2. CONTROL OF JET FLOWS

2.1 Background and Objectives

The control of jet mixing through imposition of relatively weak but carefully selected acoustic disturbances has been demonstrated by Parekh and Reynolds as part of this research program. The basic idea is to control the phasing of the large-scale ring vortex structure in the near field of the jet so as to make the rings eccentric with a spacing of roughly one jet diameter; eccentric vortex rings tilt one another, and this produces a jet with dramatically increased spreading rate and mixing. The jet can be made to *bifurcate* (divide into two separate jets) or *bloom* (explode in a shower of vortex rings), apparently at any Reynolds number and subsonic Mach number. The process is very robust and will occur in shrouded jets (*e.g.* thrust augmentors or jet ejectors).

At the initiation of this program, this flow was well understood physically and for this reason was selected as one to be used to begin to study the marriage of electronic control with fluid dynamics in the new field of flow control. The first step was to place the jet under open loop control, in which the acoustic disturbance frequencies and phases were scheduled as functions of the measured jet speed. This was easily done since the information for the schedule had been well established by the fluid mechanics research. Moreover, the resulting flow is extremely stable, so closed loop control was not necessary. Consequently, control of this flow does not require feedback, and therefore its management is extremely straightforward. Therefore, it is very nearly ready for application in practical devices, and one subtask of the current program is aimed at completing the basic data needed for application of a shrouded blooming jet to jet-ejector and thrust-augmentor systems.

However, because bifurcating and blooming jets are very robust and do not require feedback control, they are not well suited to exploration of concepts and methods for the new field of flow control. Feedback is a technique that is useful for stabilizing unstable systems, *i.e.* flows that would exist in a different state were it not for the action of the control system. On the basis of some preliminary experiments, it has been determined that a better system for study of the generic aspects of flow control is the jet emerging from a weak conical diffuser (a contraction followed by a weak divergence). With the proper selection of geometrical parameters, this flow is unstable. The instability manifests itself through transitory separation of the boundary layer along portion of the diffuser, which causes the flow to exit the diffuser in a meandering off-axis direction. We are now studying this diffuser-jet flow as the next step in developing a generic approach to flow control.

These observations lead to a conjecture about the role of feedback in flow control. If one seeks to remove an instability in a flow, for example to suppress mixing, then feedback control is essential. However, if instead one wishes to enhance an instability in a flow, for example to increase mixing, then the flow needs only to be driven with the unstable modes, and feedback is not essential. In the latter case, feedback might be used to help select the most unstable mode or perhaps even to shift the most amplified frequency. Thus, the

importance and use of feedback in flow control will depend on whether one is suppressing or augmenting the natural instabilities in the flow.

In summary, this work has as its general objective the development of a conceptual framework for active flow control. The work has two subtasks, for which the objectives are as follows:

- Control of mixing in shrouded jets

The objectives of this subtask are to determine the frequencies, phasing, and amplitudes required to produce dramatically enhanced mixing in shrouded blooming jets, and to explore various simple ways to provide the required excitation in practical devices operating at high Reynolds numbers and subsonic Mach numbers.

- Feedback control of jets

The objective of this subtask is to develop generic approaches to flow control requiring electronic feedback using jet flows as the basis for the development.

2.2 Progress to Date

a. Control of mixing in shrouded jets

This work is now being carried out by Mr. Philip Juvet under the direction of Prof. Reynolds, in consultation with Prof. Powell.

During the past year the Ph.D. dissertation of Mr. David Parekh was completed; the report version will be printed and released shortly. His work dealt with the first exploration of bifurcating and blooming jets in air, and followed on our previous work in water. We first used a simple low-speed air jet excited by four loudspeakers around the jet exit and one in the upstream plenum, and showed that a combination of axial and orbital disturbances would indeed produce these phenomena in air jets at low Reynolds numbers ($Re = 20,000$). Then, in a new high-speed air jet apparatus capable of reaching $Re = 100,000$, he demonstrated that the phenomena could be forced acoustically at high Reynolds numbers, and determined the forcing amplitudes required for a range of conditions.

Mr. Parekh is being followed by Mr. Philip Juvet, who is concentrating on blooming high Reynolds number jets in a shroud using a simple modification of the high-speed apparatus. This past year he applied hot wire anemometry to measure the flow emerging from the shroud, and showed that more than fourfold increase in entrainment can be obtained by driving the jet in the blooming mode. Figure 2.1a shows velocity profiles at the discharge of the shroud. Figure 2.1b shows these velocities multiplied by the radius, the area under these curves being the total flow rate. Note the substantial enhancement in flow over that found for the shrouded natural jet. An expanded presentation of this work will be given at the AIAA Shear Flow Control conference in March, 1989.

b. Feedback control of jets

This work is being carried out by Mr. Robert Koch under the direction of Prof. Powell, in consultation with Prof. Reynolds. The original low-speed air jet facility described above is being used in the electronic control experiments.

An electronic controller was designed and fabricated expressly for these experiments. The open-loop controller senses the plenum pressure to determine the jet exit velocity, and puts out sinusoidal signals of pre-programmed frequency, phase, and amplitude to drive the axial and orbital speakers. A number-controlled modulated oscillator (NCMO) function generator is used to generate speaker signals digitally. The NCMO function generator provides precise phase control in 4096 increments from 0-360°, precise frequency control in 0.25 Hz increments from 0-20 kHz, and continuously variable amplitudes. An important feature of the NCMO function generator is the ability to hold a constant phase between speaker channels as the frequency is changed. The NCMO function generator only requires servicing from the controller when the output signal needs to be changed, giving the control computer ample time to implement the control algorithm. It was found that the controller can place a normal jet in a bifurcating or blooming mode and hold it in this state as the flow rate is changed. The system is very robust to external disturbances, and so feedback is not required.

Using the open-loop controller in combination with smoke for visualization, two very interesting near-field jet behavior patterns have been observed clearly for the first time. For example, the helical node can be excited by using only the orbital speakers. In addition, by placing opposing orbital in-phase but 180° out of phase with the adjacent orbital speakers, elliptical vortices are generated and the round jet behaves like an elliptical jet. Thus, some new insight into the fluid mechanics has also been obtained through this control work.

Since the jet flow is so robust under open-loop control, it does not form a good basis for application of closed-loop control. Several preliminary experiments were conducted in an effort to modify the flow so as to make it unstable in a way that might be stabilized by feedback control. After some experimentation, it was found the flow emerging from a properly designed short diffuser attached to the nozzle is unstable; the diffuser section is in the "transitory stall" regime, where the main core of the flow meanders around the geometrical axis in an irregular way. Based on preliminary experiments, we believe that the flow flow can be stabilized by controlled suction at appropriate points in the diffuser section. Therefore, by placing this actuation under feedback control, it should be possible to stabilize the flow in some desired state. The diffuser-jet flow was chosen as the basis for our further research on a general approach to feedback flow control.

The test apparatus has been modified for the new control experiments. The original flow nozzle (the top of a 2 liter cola bottle), which was fine for preliminary studies but ill suited to the next phase in this work, has been replaced by a well-designed nozzle, to which various diffuser sections can be added in a modular manner. The sensors and actuators to be used in this work are described below.

2.3 Plans for Year Three

a. Control of mixing in shrouded jets

We have established that dual-mode excitation can be used to put a jet (free or shrouded) in the blooming mode, and that this results in greatly increased entrainment. While the power required for this is a very small fraction of the flow power, for large devices it is beyond the range of electromechanical actuators (acoustic drivers). Therefore, we propose to concentrate our work over the next year on finding suitable ways to use the flow itself as the primary power amplifier to produce the required disturbances.

We have a number of ideas for how this might be done, falling into three general categories. One idea that we have analyzed in some detail utilizes acoustic resonances in cavities near the jet to develop helical and axial disturbances. Calculations have suggested cavities of reasonable geometry for the present apparatus. This approach has the disadvantage that the frequencies involved are determined by the sound speed and device geometry, whereas the frequencies desired are instead determined by flow speed and jet diameter. A more promising approach to which we are currently giving attention is to use tangential blowing from a thin slot at the jet exit along a curved extension of the nozzle. The blowing controls the separation point from the curved surface, and hence the vorticity flux into the shear layer, and this in turn controls the jet. This is very similar in concept to the work described elsewhere in this report in which tangential blowing is used to control the vortical flow over delta wings; we will be able to draw considerable technology from that companion program.

b. Feedback control of jets

The jet-diffuser system will be investigated in order to determine the appropriate control actuators, sensors, and control algorithms. The idea is to use this flow to develop a basic methodology for flow control.

We must be able to cause a change in the state of the flow through control actuators. Initially we will explore actuation using various combinations of loudspeakers and (unsteady) boundary layer suction. This diffuser is equipped with eight suction slots around the circumference; since the transitory stall begins at the exit and then propagates upstream into the diffuser, these slots are located near the diffuser exit. The system also has four acoustic slots which can be driven by loudspeakers. We believe that this combination of actuators will provide effective ways to change the flow state.

The state of the system must be sensed so that the control can know what to do. We will begin by sensing only the velocity history at four points around the circumference of the jet exit using hot wire anemometers. If this does not give sufficient information for control, other sensors, probably for pressure, will be added.

In order to design a control system one needs a simple dynamic model of the flow (the "plant") and models for the sensors and actuators. The initial dynamic model of the

sensors and actuators will be based on a linear, finite- dimensional model of the way that the system responds to perturbations about a target state.

The experiments will begin with use of parametric and non-parametric system identification techniques to obtain the dynamical model. Based on this information, a multi-input, multi-output control algorithm will be designed to stabilize the system. If this is successful a command-following control will be implemented which hopefully could, for example, set the direction of the emerging jet. Classical techniques and modern methods including *loop transfer recovery* will be used to develop the control algorithm.

The control algorithm will be implemented on a dedicated digital controller. A very high speed processor will be needed to calculate the control algorithm in real time. The bandwidth required of the control system is believed to be on the order of 100 Hz which would require the control algorithm to be processed at approximately 1000 Hz. Our plan is to carry out the real time control on a 80386 based controller under the supervisory direction of a UNIX based workstation.

2.4 Participants

Faculty Co-Principal Investigators:

Prof. W.C. Reynolds (fluid mechanics)

Prof. J.D. Powell (automatic control)

Graduate Research Assistants:

Mr. David Parekh (Ph.D. Fall 1988)

Mr. Philip Juvet (Ph.D. expected 1990)

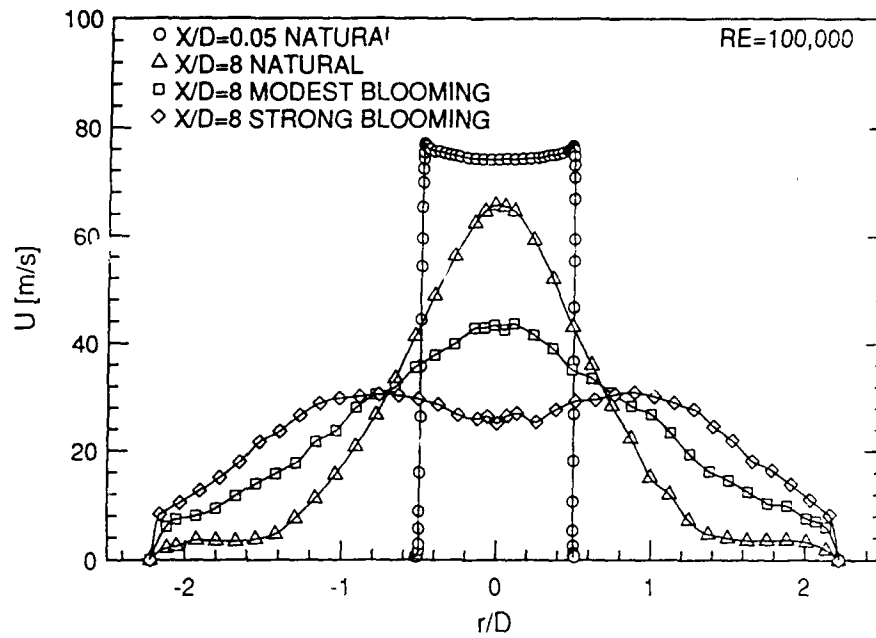
Mr. Robert Koch (Ph.D. expected 1990)

2.5 Publications to Date

PAREKH, D., P. JUVET, and W.C. REYNOLDS, *Bifurcating Jets at High Reynolds Numbers*, 6th Symposium on Turbulent Shear Flows, Toulouse, France, September 1987.

JUVET, P. and W.C. REYNOLDS, *Entrainment Control in an Acoustically Controlled Shrouded Jet*, AIAA Symposium on Flow Control, Tempe, Arizona, March 1989.

SHROUDED JETS VELOCITY PROFILES



ENTRAINMENT IN SHROUDED JETS

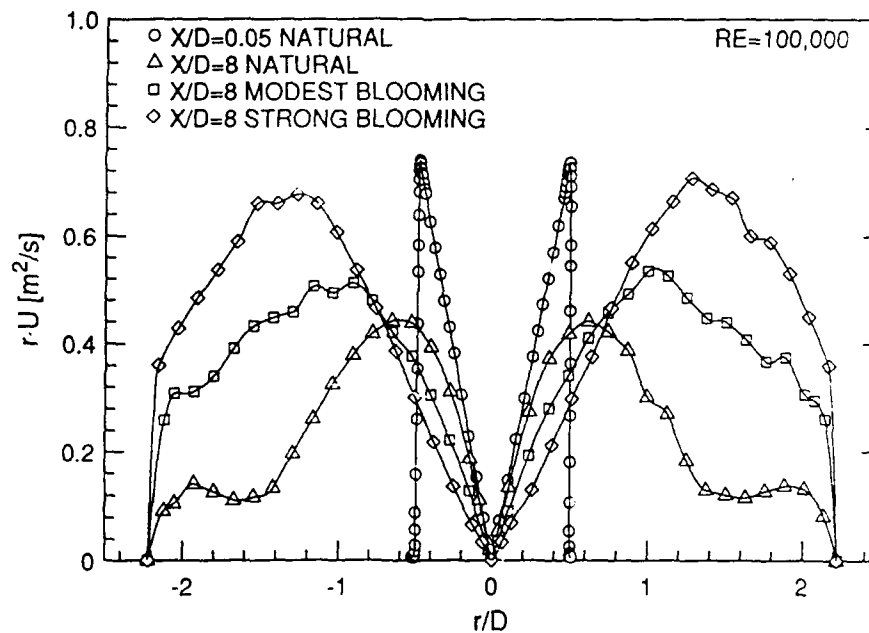


Figure 2.1 Entrainment Data for Shrouded Jets

3. ACTIVE CONTROL OF UNSTEADY SEPARATING FLOWS

3.1 Background and Objectives:

Unsteady separated flows are dominated by large vortex structures which are the focus of modern control efforts. The rollup, growth, and eventual shedding of large spanwise vortices are the most significant events in two-dimensional unsteady separated flows and are probably also important in moderately three-dimensional flows. An effective control system must have the ability to sense and/or predict the presence, strength and location of the vortices and to modify the vortices in appropriate ways.

The evolution of a spanwise large vortex is governed by the vorticity flux from upstream, the motions of the separation line where upstream vorticity moves away from the surface, loss mechanisms which remove vorticity from the primary vortex, and of course the boundary conditions which control the potential flow. Strong changes in the vortex development can be achieved by radically altering the boundary conditions, *e.g.* oscillating an airfoil. Practical control schemes will require that the vortex evolution be modified using more modest inputs. For example, it is possible to increase the rate of vorticity loss from the vortex by introducing three-dimensional disturbances. Alternatively, it may be possible to modulate the flow of vorticity into the separation region using relatively small upstream disturbances. While it is not clear that any technique other than large boundary condition changes will be effective at substantially modifying the unsteady vortex development, there are a few unexplored alternatives.

The present research program is examining active feedback control of unsteady separating flows. There are several key problems which stand in the way of true feedback control of such flows. One problem area is how to apply modern control theory to a strongly nonlinear system which exhibits very large hysteresis. One approach is to use adaptive control theory which essentially allows the plant model to change with time. This approach has been successful for simple geometries but may not work well in complex geometries. Our approach is to identify or predict the dominant vortical structure first and then choose the appropriate reaction. The second problem then is how to sense the vortex structure in real-time and predict the future time evolution using the known flow state and control inputs. A third problem is how to design a control system which can account for convective delays of control inputs. Many proposed control systems for unsteady separated flows involve input of disturbances upstream of the separation point, so there is a finite convection time before the control disturbance arrives at the separation point. This is simple to account for in periodic flows but may cause difficulty in non-periodic flows. Finally, there is the underlying problem of developing control inputs which can effect the vortex evolution.

Two very different types of control inputs (actuators) are under consideration in this program. The first idea is to introduce spanwise vorticity of the proper sign and phase in an effort to control the primary separation vortex. The second approach is to use streamwise vortices, introduced by wall-mounted half-delta generators and articulated on command, to control what would otherwise be a two-dimensional separation. The development of

information about the transient nature of these streamwise vortices is a needed first step in consideration of this second method of active separation control.

The present research program is a two-part effort, both of which are funded by AFOSR, under the direction of Prof. Eaton. The first part of the program (AFOSR-86-0159) had the objectives of understanding the physics and developing a control scheme for the unsteady flow behind a lifting flap. Part of the budget for this program was folded into the present URI grant. Additional funding in the URI is for the study of actuated longitudinal vortex generators used to control smooth wall separation.

The overall objectives of the program are as follows:

1. to understand the physics of unsteady separating flows with an emphasis on identifying mechanisms which may be used to control the flow;
2. to develop techniques for the real-time identification of vortex structures in the flow;
3. to develop an active control scheme for the lifting flap flow;
4. to study the development of the flow behind an actuated vortex generator; and
5. to develop a technique for active control of smooth wall separation.

3.2 Progress to Date

This section describes the progress on segments of the program which are funded by the URI Grant. Some reference to work under the companion AFOSR contract is necessary.

Detailed LDA data measured in the lifting flap flowfield has shown that virtually all of the vorticity passing the separation point is rolled up into the vortex and remains until the vortex is shed. Loss mechanisms due to naturally developed three dimensionality and turbulence are insignificant. Attempts to augment the loss mechanisms using two and three dimensional perturbations have produced only small changes in the temporal evolution of the vortex. This leads us to the conclusion that the only possible ways to modify the lifting flap flowfield are through modulation of the vorticity flux into the separation region, removal of vortical fluid from the separation region, or the introduction of opposite signed vorticity in the vicinity of the primary vortex.

We are attempting to control the lifting-flap flow using a second spanwise flap located either upstream or downstream of the primary flap. The proposed geometries are sketched in Figure 3.1. The idea of the upstream flap is to modulate the flow of vorticity into the primary flap vortex. The idea of the downstream secondary flap is to introduce vorticity of either the same or opposite sign as the primary vortex into the vicinity of the primary vortex. A new wind tunnel with a larger test section was needed to conduct these experiments which are expected to involve very large scale vortex interactions.

During the past year construction and qualification of the Flow Control Wind Tunnel has been completed and the flow quality in the 2 ft. by 3 ft. test section has been checked. A computerized control system for both the wind tunnel speed and temperature and the probe traverse system is installed. A test plate has been fabricated and installed into

the wind tunnel. A new flap drive system was developed which allows great flexibility in positioning the two flaps. The larger, primary flap has a 5 cm chord length and can be oscillated at frequencies up to 12 Hz for full 0 to 90° actuation. The control flap has a 2.5 cm chord and can be positioned either upstream or downstream of the primary flap and facing either forward or backward. This control flap can be oscillated at frequencies up to 60 Hz with limited amplitude, but will ordinarily be actuated at frequencies approximately equal to the primary flap frequency. Smoke-wire flow visualization hardware has been completed with the control flap oscillating at the same frequency as the primary flap at various phase shifts. Drastic changes in vortex size and structure have been observed. This work is presently being extended to higher control flap frequencies.

The second set of experiments, conducted exclusively under URI funding, is an examination of the use of actuated longitudinal vortex generators for the control of smooth wall separation. The generators are surface mounted, half- delta wings which are actuated using a printed circuit motor. The first step in this experiment is to examine the temporal structure of the flow downstream of the generator following an actuation. Important questions to be answered are: What is the initial structure formed during the actuation? How rapidly does the longitudinal vortex form? What is the propagation velocity of both the initial structure and the longitudinal vortex?

The full spatial and temporal development of the flow has been examined for two different vortex generators mounted in a zero pressure gradient boundary layer wind tunnel. The smaller generator with a chord length of 5 cm and a height of 2 cm is fully embedded in the turbulent boundary layer. The larger generator, 10 cm by 4 cm protrudes well out of the boundary layer. Each generator is actuated from 0 to 18° degrees in approximately 10 ms. All three velocity components are measured downstream of the generator using a rotatable cross-wire anemometer probe as illustrated in Figure 3.2. Data are measured in planes of approximately 60 points at each of four axial stations. The data are processed in real-time using the Masscomp 5400 laboratory computer then displayed and interpreted using a Silicon Graphics IRIS workstation.

Data for the larger generator are shown in Figures 3.3 and 3.4 for a plane located 28 cm (2.8 chord lengths) behind the center of the vortex generator. The freestream velocity was approximately 12.5 m/s for the case shown. Figure 3 shows the longitudinal vorticity in $Y - Z$ planes as a function of time. Only one-fifth of the available time steps are shown for clarity. The development of the vortex is very rapid going from non-existent to almost fully developed in a non-dimensional time (tU/L) of 1.08 where L is the generator chord length. Contours of axial velocity (not shown here) show that the boundary layer distortion develops rapidly so that the boundary layer is strongly distorted as soon as the vortex appears. Data from the downstream planes 3.4 and 5.9 chord lengths downstream show that the longitudinal vortex decays very slowly.

Contours of the vorticity component normal to the wall are shown in Figure 3.3. A startup vortex passing the measurement plane at early times is the first feature observed. In contrast to the longitudinal vortex, this startup vortex diffuses rapidly and is found to be much weaker at the furthest downstream station. The propagation velocity and initiation

time for the startup vortex may be estimated by plotting the time the vortex passes each measurement station. Figure 3.5 shows such a plot for the larger vortex generator. The figure shows that the propagation velocity is approximately 95% of the freestream velocity and the vortex sheds almost immediately upon actuation. Similar plots for the leading edge of the longitudinal vortex show that its propagation velocity is also close to the freestream velocity.

Measurements for the smaller vortex generator which is fully embedded in the boundary layer show a qualitatively similar structure except the starting vortex is not observed. The starting vortex would be expected to diffuse very rapidly when embedded in the turbulent boundary layer. The longitudinal vortex propagation velocity is somewhat slower as would be expected.

The next step for the actuated vortex program is to study the development of the vortex in an adverse pressure gradient wind tunnel. A special purpose wind tunnel for the study of control of adverse pressure gradient boundary layers was constructed in conjunction with Professor J.P. Johnston. The tunnel, which is described in Section 4 of this report has now been fully qualified and used successfully for controlled boundary layer studies. The tunnel configuration is very flexible so the actuated vortex generators can be installed easily.

3.3 Plans for Year Three and Beyond

The primary work on this project over the next two to three years will be on the active control of smooth wall separation using actuated longitudinal vortex generators. The first step is to examine the performance of the actuated vortex generators in a steady adverse pressure gradient flow. A new mechanism has been designed to actuate a row of 6 half delta generators to produce an array of counter-rotating vortex pairs. The array will be mounted at station L1 in the Adverse Pressure Gradient Wind Tunnel (see Figure 4.1). The tunnel will be set up for a moderate adverse pressure gradient producing separation near station L3.

The first experiments will examine a steady flow with actuated longitudinal vortex generators in fixed position to determine the required control input to maintain fully attached flow. The diagnostics in this phase will be pressure measurements and reverse flow intermittency using our thermal tuft flow direction sensors. Both types of measurements are simple and can be performed rapidly.

The next set of experiments will examine the temporal development of the flow after vortex generator actuation and upon removal of the control input. The major questions to answer are i) can the actuated vortices cause a fully separated boundary layer to reattach? ii) If so, how is the vorticity that was contained in the separation vortex shed? iii) What are the time scales involved in reattaching the separated boundary layer? iv) How rapidly does the separation region build up when the vortex generators are returned to a neutral position? and v) Is the initial development of the separation region similar to that in other

unsteady separated flows? These questions will be studied using smoke wire flow visualization, phase-conditioned pressure and flow direction measurements, and where possible, hot-wire anemometry.

The final experiments, before proceeding to study of full feedback control, will examine the flow development behind oscillating vortex generators. We believe that the actuated generators will cause the spanwise separation vortex to wash out fairly rapidly. Conversely, there is expected to be a significant lag in reforming the unsteady separation vortex when the generators are turned off. Therefore, oscillation of the generators with an asymmetric waveform may produce a series of moderate scale spanwise vortices rather than one large vortex or a fully stalled flow. The work in this phase will be primarily flow visualization with some pressure measurements. We will probably have to test a number of frequencies and oscillation waveforms before arriving at flows which may be desirable for control implementation.

Subsequent work on the project would involve computerized feedback control of the entire system. The project would be integrated with our work on real-time sensing of vortex structures but would include sensing and or prediction of either incipient detachment or full detachment of the boundary layer. Sensing of incipient detachment may be possible using either thermal tuft probes which can detect small scale instantaneous flow reversals, or closely spaced pressure measurements for real-time measurement of the pressure gradient. The Adverse Pressure Gradient Wind Tunnel will be modified for this phase of the work to allow the application of an unsteady adverse pressure gradient to the boundary layer.

Work during the coming year on the lifting flap program will concentrate on testing the controllability of the flow using the secondary flap in both the upstream and downstream positions. The first set of experiments will examine the flow around a sinusoidally oscillating main flap with an upstream control flap oscillating at the same frequency. The main parameter of interest will be the relative phase angle between the two flaps. Smoke wire flow visualization and phase-conditioned pressure measurements will be used to investigate the vortex development and the role of upstream vorticity flux modulation.

The main emphasis of the program will be on the control of the flow in a situation where the main flap is pitched to a large angle then held in that position. Both upstream and downstream flap configurations will be tested and a variety of control flap waveforms will be used based on the results of the first phase of work. There will be two primary control objectives in this phase; i) maintaining the presence of the unsteady spanwise vortex for the longest possible duration, and ii) causing the vortex to shed at a precisely controlled time. Achievement of the first objective would allow exploitation of the advantageous characteristics of dynamic stall. The second objective is more focused on maintaining vehicle control during a dynamic stall event by synchronizing vortex shedding from the two wings.

The final piece of work planned for the coming year is the development of real-time hardware and software for vortex identification. To date, we have used phase-conditioned pressure measurements taken from 9 stations downstream of the flap to validate our vortex recognition algorithm. The results have shown that the pressure signals can be used

effectively but do not show if the data processing can be done in real time. Real-time identification requires rapid data acquisition and reduction from multiple pressure sensors. This work in particular will examine the computer and instrumentation requirements for real-time identification at realistic flow speeds. Considerable simplification of the algorithms may be required. The capital equipment item on the budget is for the purchase of an array of fast response pressure transducers.

Work in subsequent years will focus on feedback control of the flap flow to achieve a range of desired flow conditions. Details of the work will depend on the results of the coming years work.

3.4 Participants

Professor J.K. Eaton, Principal Investigator

Dr. Dennis J. Koga, Senior Research Associate

Mr. Howard Littell, PhD Student (PhD expected 1990)

Mr. Edwin Noma, MS Student (MS expected 12/88)

This work is closely coupled to the work being done by Mr. Curt Nelson (PhD expected 1989) and the work supervised by Professor J.P. Johnston on vortex generator jets, described in Section 4 below.

3.5 Publications

EATON, J.K., J.P. JOHNSTON and D.J. KOGA, *Active Control of Separating and Fully Separated Flows*, Proceedings of 1988 AFOSR Contractors Meeting on Turbulence, USC, July 1988.

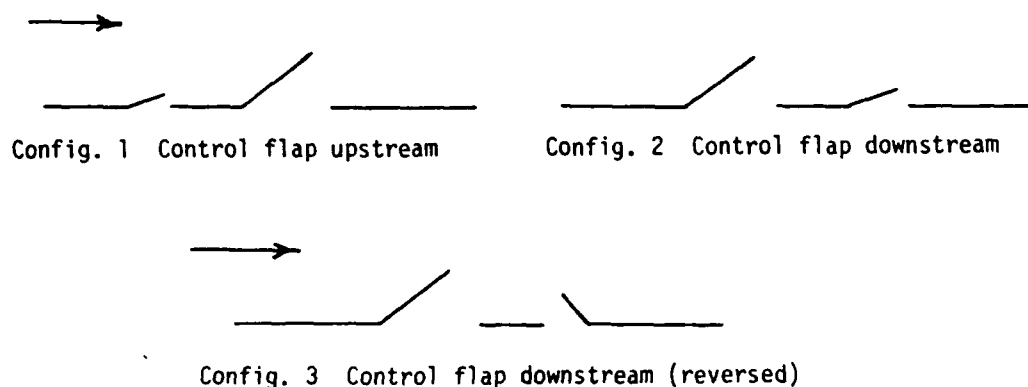


Figure 3.1 Configurations for the Two Flap Experiments.

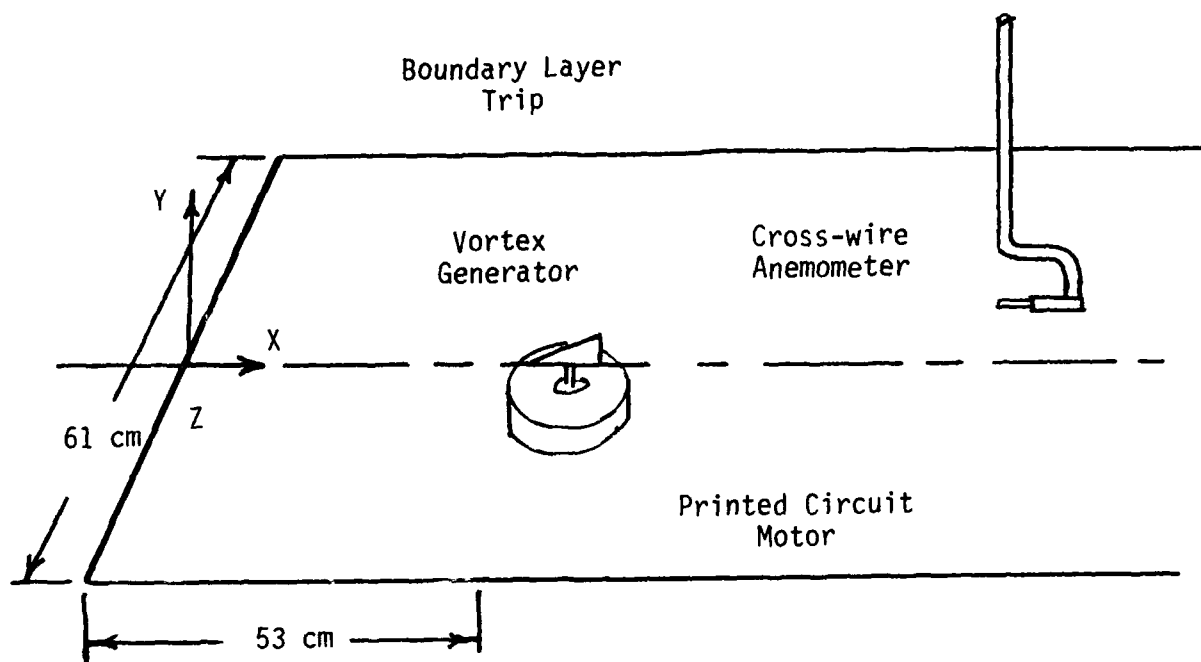


Figure 3.2 Schematic of Actuated Vortex Experiments.

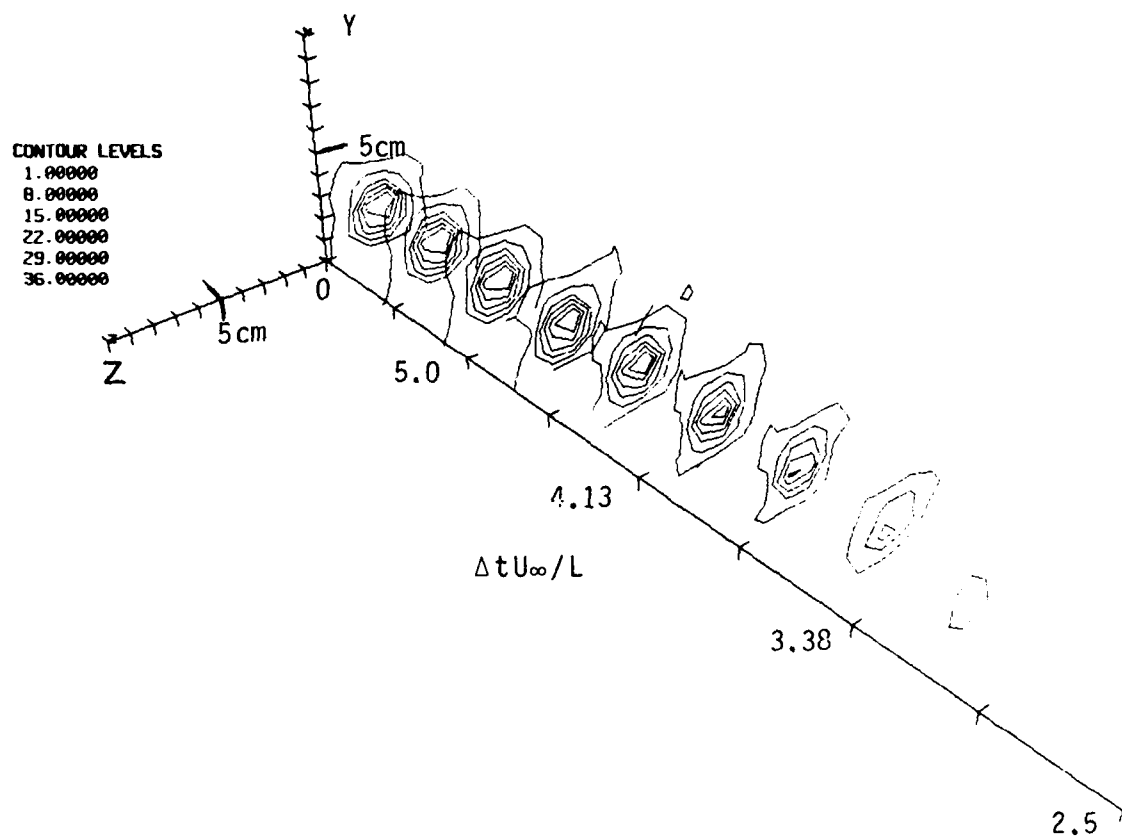


Figure 3.3 Longitudinal Vorticity Behind Actuated Vortex Generator.

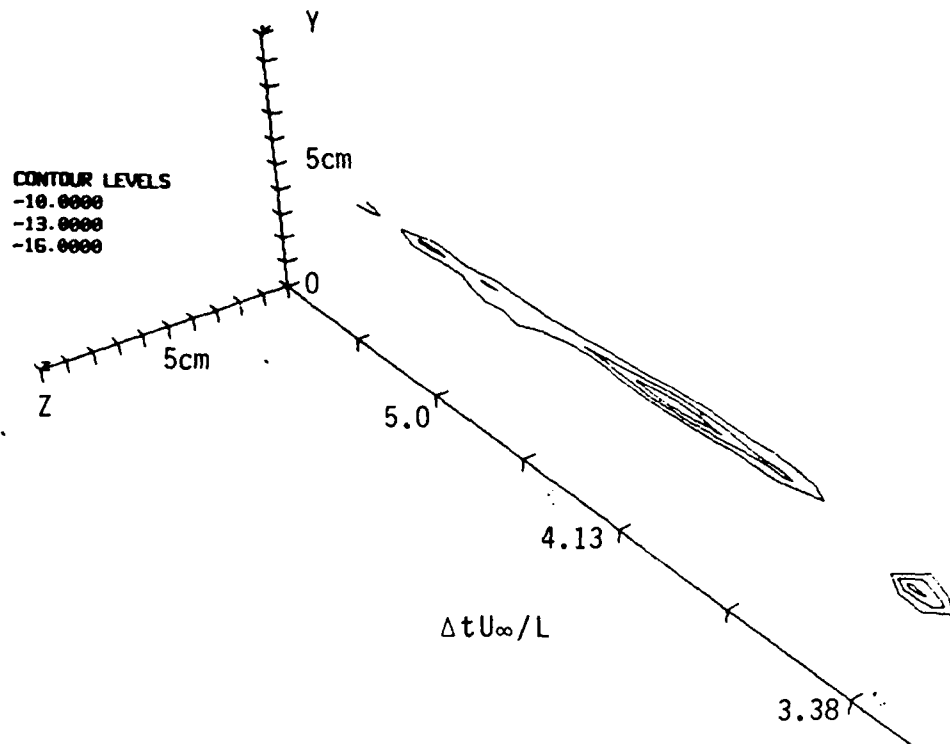


Figure 3.4 Y-Component Vorticity Behind Actuated Vortex Generator.

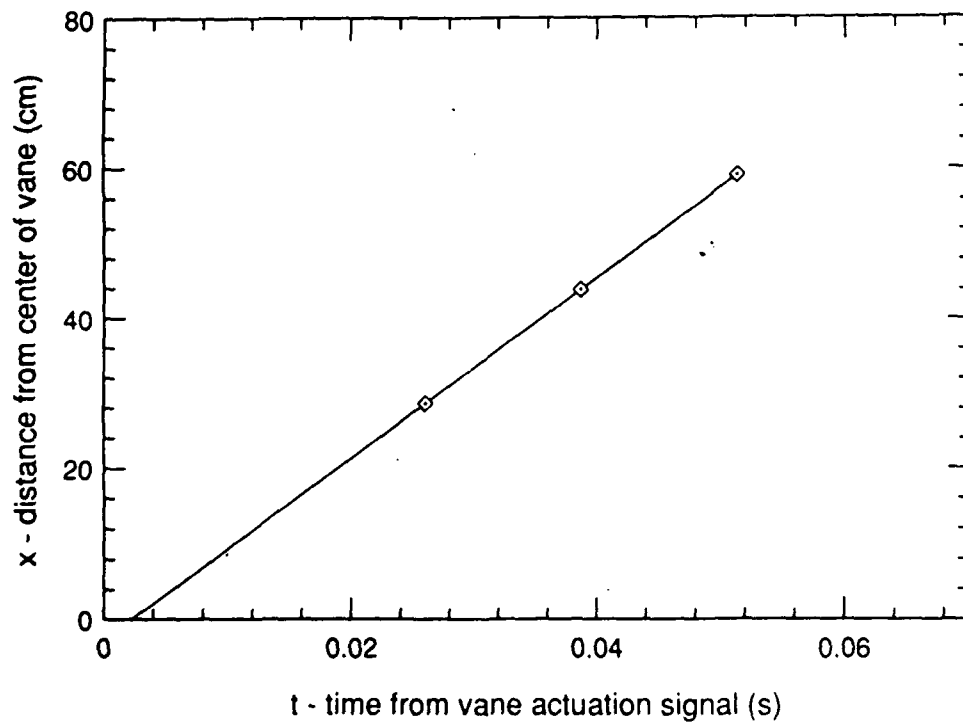


Figure 3.5 Position of Startup Vortex as a Function of Time.

4. VORTEX GENERATOR JETS FOR BOUNDARY LAYER CONTROL

4.1 Background and Objectives

This program is being carried out under the direction of Professors Johnston and Eaton. We are investigating the feasibility of and the design parameters for a stall (flow separation) control method denoted as the vortex generator jet (VGJ) method. The VGJ method employs spanwise arrays of small jets injected through surface holes into a boundary layer. The injection holes are located upstream of, or in the adverse pressure gradient zone ahead of a region of separation (a stalled zone). When properly designed, the jets, like fixed vortex generators winglets, are capable of causing the downstream development of streamwise vortices. The vortices mix free-stream momentum into the boundary layer, energize its retarded inner layers, and thereby delay or eliminate flow separation, *i.e.* stall is controlled.

This idea, first proposed and studied by Wallis (1952-60), has not been employed to this day. The feasibility has not been firmly established, but if feasible, the idea should have marked advantages over solid vortex generators for active flow control on aircraft surfaces, and in jet engines. Jets are easy to actuate, and should be fast to respond in situations where rapid and controlled modulation of the state of separation and stall is desired. Also, compared to solid generators, the drag or loss penalty of VGJs is negligible when the jets are off. This represents an important consideration when cruise speed and operating range of an aircraft is considered. Because it is easily controlled, the VGJ method might also be used for reduction of flow distortion from jet engine inlet diffusers during high angle of attack maneuvers. Other diffuser applications are also anticipated.

Our work is experimental, carried out in our newly reconstructed, low-speed, turbulent-boundary-layer, wind tunnel. The first phase, now underway is investigating the feasibility of Wallis' idea and some new ideas of our own. The design parameter matrix of the concept will be explored next, and a clearer picture of the physical mechanisms developed. Finally, in the last part of the work (follow on to the current three-year program) detailed measurements on the structure and turbulence in selected, prototypical cases will be carried out to check on an engineering design and performance prediction method to be constructed in conjunction with the experiments.

The specific objectives are as follows:

1. Reconstruct the nozzle and test section of a low-speed air test facility, and acquire a Masscomp data acquisition computer (jointly with the project described in section 3). This was completed in year 1 of the program.
2. Build and test a VGJ injection and measurement system (year 2).
3. Conduct preliminary tests to demonstrate that longitudinal vortices are produced by the VGJ in a turbulent boundary layer jets when they interact with the layer (year 2).
4. Prove that the VGJ system is capable of causing a detached, two-dimensional, turbulent boundary layer to reattach (year 2).

5. Investigate the effects of changes in flow and design parameters on the ability of the VGJ system to affect reattachment (years 2 and 3).
6. Develop a working model of the mechanisms responsible for the VGJ effectiveness and an engineering design system for practical implementation (year 3 and beyond).

4.2 Progress to Date

We have conducted a series of experiments in the recently reconstructed nozzle and test section for an existing, two-dimensional, boundary layer wind tunnel. In the 610 mm wide by 127 mm high inlet area of the test section we can produce a two-dimensional, turbulent boundary layer with a momentum thickness Reynolds number $= 1400$, and $d = 15$ mm. This condition is obtained with a 15 m/s free-stream tunnel speed at the beginning of a region of adverse pressure gradient.

Using a flexible opposite (top) wall, the pressure gradient can be manipulated to separate, or detach (D) the boundary layer on the flat-walled test surface, and if required, make it reattach (R) on the aft end of the test surface. The nozzle and test section are shown in Figure 4.1.

At station L1, a row of six small jets, the VGJs, spaced 102 mm apart along the span, issue from the test surface through 6.4 mm diameter holes. The hole spacing to diameter ratio of 16:1 is the largest to be investigated. Smaller spacing ratios may be studied later. The row of VGJ holes is close to the streamwise location of the top-wall suction scoop on the as indicated in Fig. 4.1, and 150 mm ahead of the flexible top wall. Each VGJ hole is drilled with a slant inclination (pitch) angle of 45° to the wall through six separate, flush mounted brass plugs. Each plug can be rotated to produce an arbitrary jet skew (cross-flow) angle with respect to the tunnel main flow direction, the streamwise x -direction. Air for the jets is delivered by a separate air pump to a plenum box under the test surface at location L1 from whence it flows through the jet holes to form the VGJs in the test surface boundary layer. The air is metered and controlled to enable us to set various velocity ratios (jet speed to local free stream velocity, $V_R = V_j/U_\infty$, up to about 1.4).

In one series (counter-rotating) of experiments the jet skew angles were set alternately at $\pm 90^\circ$ to the tunnel axis (flow direction). In another series (co-rotating), following Wallis' suggestion, all six jets were skewed at $+90^\circ$ to the main flow, pointing in the same direction. A third series was also carried out to see if setting the jets to an 180° angle, pointing directly upstream would be effective. In each set of experiments, the jet velocity ratio, V_R , was varied in steps over a range from 0 to 1.

In preliminary experiments with the counter-rotation configuration, before a adverse pressure was applied by deflecting the flexible, top tunnel wall, we attempted to answer objective (3). Detailed surveys of the spanwise distribution of skin-friction were obtained using the Preston tube method. A small stagnation tube was traversed across the test surface at two downstream locations, L2 and L4, for three flow conditions: A, no jet blowing; B, mild blowing at $V_R = 0.4$; and C, strong blowing at $V_R = 1$. The results

documented in Figures 4.2a and 4.2b show the same patterns of peaks and valleys in the spanwise distribution of C_f as seen in the recent experiments by Pauley and Eaton with spanwise arrays of small delta-wing shaped vortex generators. In the figures, each peak and valley corresponds to one of the four VGJs within the 400 mm span of the traverse. Mean velocity surveys obtained for various spanwise locations at station L2 confirmed that the VGJs interact with the boundary layer and generate longitudinal, streamwise vortices that persist downstream in a turbulent boundary layer, at least when the jets are injected across the flow at angles close to 90° . The sketch in Figure 4.2b shows the approximate locations and signs the vortices at station L4, relative to the jet locations and directions at station L1. These results answer Objective 3. Yes, VGJs can produce streamwise vortices.

Following the preliminary experiments to demonstrate that streamwise vortices can be created, we impressed a strong adverse pressure gradient on the flow downstream of station L2, and caused full detachment (D) at $x = 680$ mm just downstream of L3. x is measured from zero at station L1. As the pressure gradient relaxed behind D, reattachment (R) occurred at $x = 1380$ mm, between stations L5 and L6. The detachment and reattachment locations are obtained by the use of one of our *thermal tuft* plugs. The plug fits into holes spaced every 152 mm along the centerline of the test surface and permits the determination of the streamwise profiles of forward flow fraction, γ , in the sublayer of the boundary layer. At both D and R, γ is 0.5 (backflow 50% of the time). Values of γ as low as 0.07 (backflow 93% of the time) were seen in the separated zone, between D and R. Detailed static pressure profiles expressed as a pressure coefficient, $C_p = 2[p(x) - p(0)]/(\rho U_\infty^2)$, along the test surface further confirmed our observations. C_p rose to about 0.46 at D, held a constant value for a while, and then rose slowly in the region of reattachment to about 0.57 at R, see Figure 4.3, jets off case. This behavior is very typical of a spanwise two-dimensional turbulent separation bubble.

The experimental C_p data with no jet flow, and other controlled cases are compared to the ideal, attached loss profile in Figure 4.3. Arrays of small, delta shaped wing vortex generators are used on the duct's side and top walls to prevent stall on those surfaces (locations indicated in Fig. 4.3). The changed shape of the pressure coefficient profile with counter rotating jets shows the effectiveness of the VGJ method. The thermal tufts show partial stall suppression at 0.6, and nearly complete 100% forward flow at $V_R = 1.0$. Change to the co-rotating configuration effects these results very little, but with the jets skewed at 180° (directly upstream) there was hardly any separation suppression at any location. Apparently in this case, no longitudinal vortices are produced. These and other similar results meet objective 4. They show that turbulent boundary layer separation can be suppressed.

4.3 Plans for Year Three and Beyond

We plan to complete the research needed to meet the first four specific objectives listed above in section 4.1 by the end of year three. This work can be accomplished with the assistance of a master's degree candidate working part time during the academic year and

full time in the summer of 1989. Some progress can also be made on objective 5, a study which explores the design parameter space of the VGJ concept in greater detail. These results are needed in preparation for future work, the follow on program recently proposed to Naval Air Systems (G. Derderian).

In general, the future appears bright for potential applications of the VGJ concept. So far our studies have concentrated on the simplest form of the concept, steady flow stall control of a subsonic, low Reynolds number, two-dimensional turbulent boundary layer. A number of other ideas need to be investigated. These include (i) use of periodically pulsed jets to improve jet-air consumption efficiency, (ii) tests of the VGJ concept for suppression of steady three-dimensional stall, (iii) examination of VGJs response and time-delay characteristics in regard to their application to unsteady two- and three-dimensional stall control, (iv) applicability to dynamic (rotating stall and surge) control in jet-engine compressors, (v) use of VGJs at subsonic and supersonic conditions including their influence on shock boundary layer interactions (note: This was a thrust of early work by Wallis). It is also essential to examine the method under more realistic conditions, first with wind tunnel models and eventually in flight and/or engine tests.

We consider long term, follow-on research at several levels essential to the viability of this concept. Basic work, which carry forward from the current studies can be carried out in our laboratory, items (i, ii, and iii) above in particular. At Stanford we are well equipped to examine the physics of the flow and develop analytical and computational models of the flow which will be needed to guide engineers as they attempt to apply the VGJ method. Work at high Reynolds number, at free-stream Mach numbers larger than 0.15 to 0.2, and the large scale, applied research leading to applications would be better conducted in major laboratory such as AFWAL or one of the NASA labs. Because of the proximity of NASA/Ames Research Center and Stanford, Ames would be the preferred location for this work.

4.4 Participants

To date in addition to the P.I's. we have had the active participation of Professor M. Nishi, a visitor from Kyushu Institute of Technology for nine months in 1987/88 who helped in tunnel development, objectives 1 and 2, and the demonstration that the VGJs form streamwise vortices, objective 3. Mr. D. Coffey, a summer research assistant, was responsible for data acquisition and analysis for objective 4, the proof that the VGJ method could control stall. Assistance has also been provided by Dr. D. Koga, Senior Research Associate on the project, and Mr. H. Littell, a first year grad student (Ph. D. in June 1991).

4.5 Publications to Date

JOHNSTON, J.P. and M. NISHI, *Vortex Generator Jets - A means for Passive and Active Control of Boundary Layer Separation*, Paper no. 89-0564, 27th Aerospace Sciences Meeting, Reno, January 9-12, 1989.

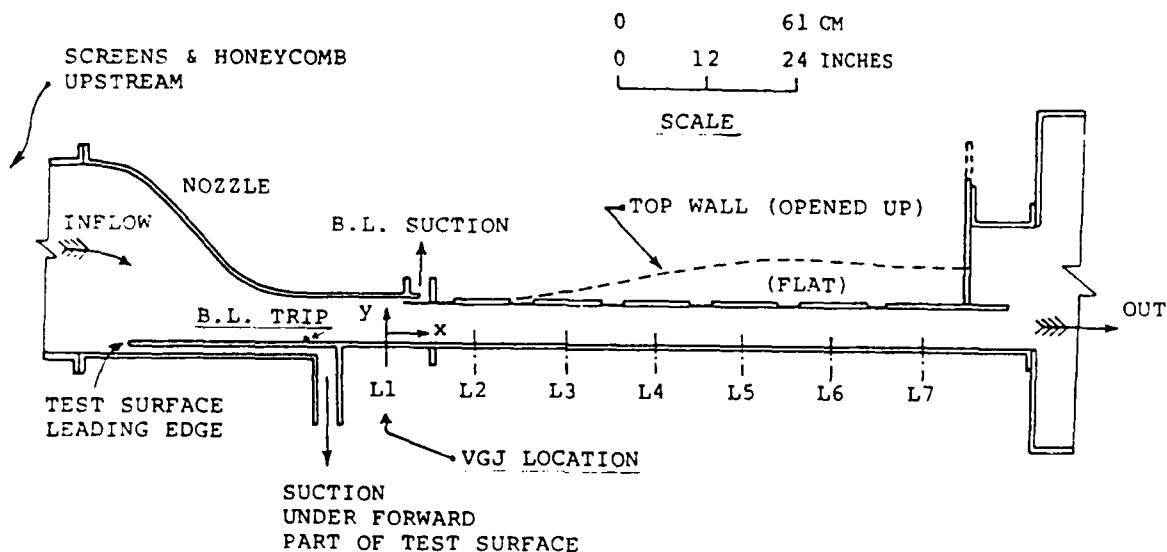


Figure 4.1 Wind tunnel test section (61 cm wide). VGJs at $x = 0$, station L1.

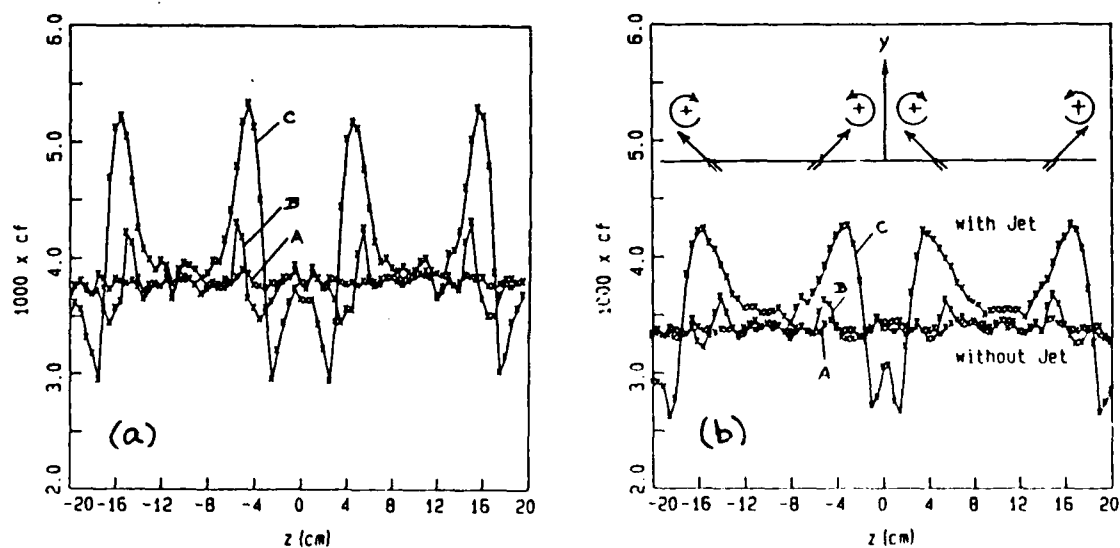


Figure 4.2 Skin friction coefficient versus span, z . (a) station L2, and (b) station L4. Curves: A, $V_R = 0$, no blowing; B, $V_R = 0.4$; C, $V_R = 1.0$.

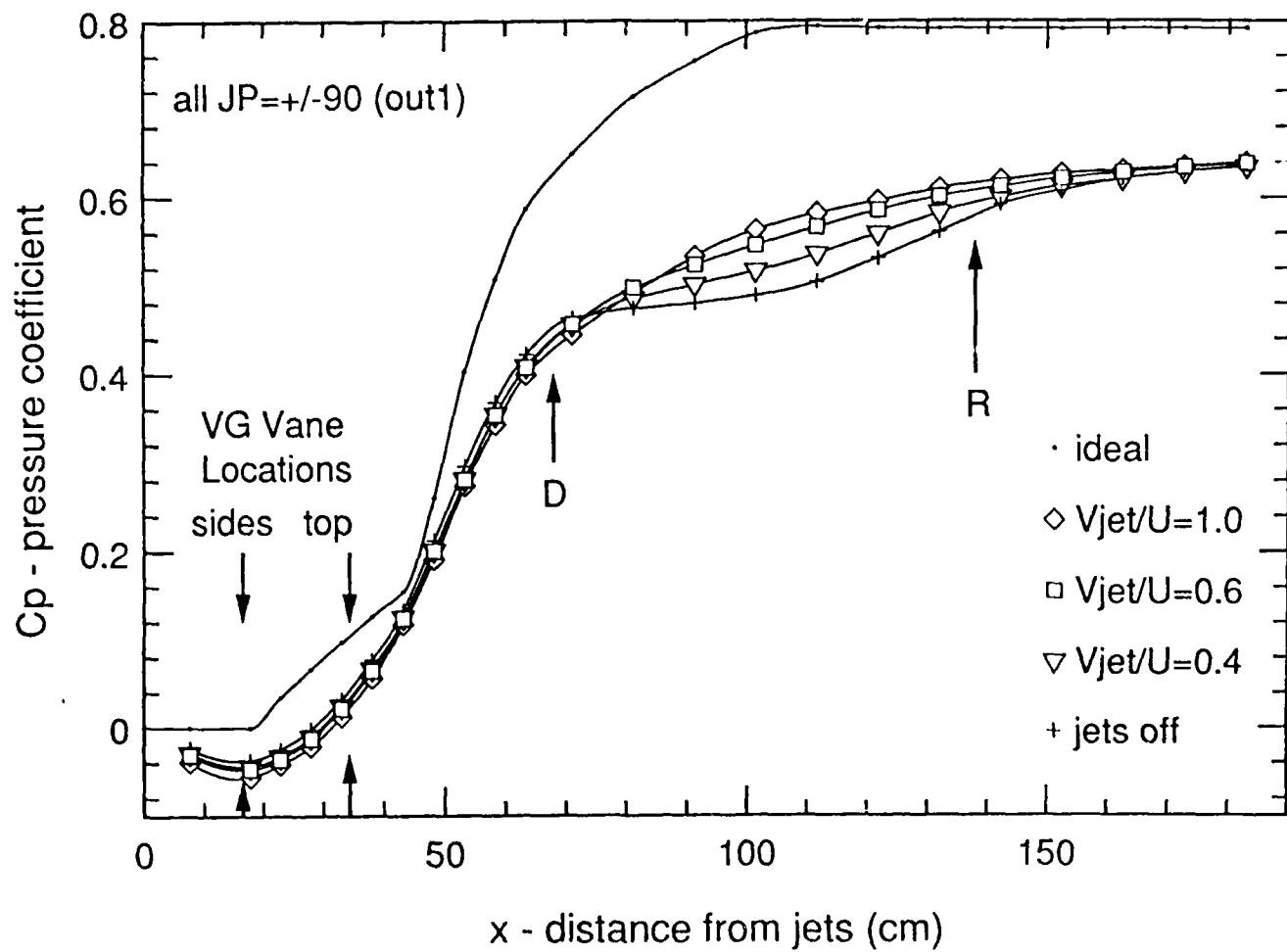


Figure 4.3 Static pressure coefficient versus downstream distance.

5. ACTIVE CONTROL OF UNSTEADY BOUNDARY LAYERS

5.1 Objectives and Approach

For the past two years we have been investigating the control of an unsteady turbulent boundary layer on a flat plate by vortex generators mounted on the surface. The objective has been to understand the physical processes by which streamwise vortices, put into the boundary layer by the vortex generators, modify the transient response of the boundary layer to a sudden change in free-stream velocity gradient and thereby inhibit separation.

The work is being carried out by AF Major William Humphreys under the direction of Prof. Reynolds, and is one of three parallel projects taking place in unique unsteady flow water channel. The channel (Figure 5.1) is capable of imposing a known and well-controlled unsteady free-stream variation on the test boundary layer at frequencies up to 40 Hz. The flow leaves the channel through special computer-controlled valves that can be positioned anywhere along the channel wall opposite to the test surface (the control wall). By increasing the flow through a valve in the control wall opposite the test region while making a compensating reduction in the flow through another valve far downstream, the flow through the channel upstream of the test region can be maintained steady, and a strong adverse pressure gradient imposed on the boundary layer in the test region. The waveforms of these disturbance can be arbitrary. In the present experiments we switch the free-stream condition back and forth between a condition of zero pressure gradient and strong adverse gradient.

The flow speed is in the range 0.1-1 m/s, allowing laminar experiments near the front of the test plate or turbulent experiments near the end. The water temperature and air content are precisely controlled so that experiments are very repeatable. A three-component LDA system is used for velocity measurements, and a wall-fan-fringe optical skin friction measurement system (developed by our group) is available. The system operates under computer control, which permits ensembles of data to be collected over long periods (e.g. a week) with minimal operator intervention.

5.2 Progress to Date

Major Humphreys has completed the data for his Ph.D. dissertation, now being written. He has mapped out the phase-average velocities, turbulent stresses, and vorticity in the turbulent boundary layer after the onset of the adverse pressure gradient for two conditions: 1) vortex generators at zero angle of attack, and 2) vortex generators at $\pm 18^\circ$, where he concentrated on the spanwise region where the flow induced by the vortices is towards the surface. The measurements were made at a point near the end of the region of adverse pressure gradient.

Figure 5.2 shows an example of data he obtained that would be important for the design of a control system for this flow. We plot the ratio of the deviation from the final value to

the initial deviation (which starts at 1 and goes to 0) *vs.* time from the onset of the adverse pressure gradient, non-dimensionalized by the time it would take a fluid particle in the free stream to travel from the start of the pressure gradient to the measurement point. These data were taken on the centerline between the common-flow-down vortex pair. The open points are with feathered generators and the solid points are with the half-delta generators inclined 18° to the flow. The data provide two important control parameters; the *delay time* before the response is felt, and the *response rate* (slope of the semilog curve) of the (linearized) response.

The curves of Fig. 5.2a are for the near-wall region. Note that the response is immediate, indicating that the pressure field (and not convection) dominates the near-wall region. Moreover, the response rate (curve slope) is not significantly affected by the vortex generators. In contrast, the curves of Fig. 5.2b for the outer region of the boundary layer show that the outer region response is delayed, indicating that this region is dominated by convective processes. Note that the delay time is increased by the vortex generators, but the post-delay response rate with vortex generators is much faster.

There is an important message here for flow control. Time delays make flow control very difficult. However, because the near-wall flow is dominated by pressure changes, a near-wall sensor can detect an upstream event *before* the event has been convected to the sensor. This suggests that flow-control sensors should be placed in the near-wall region in order to have the earliest possible warning of a needed control action.

These experiments proved very difficult to perform because of the very long times required to collect adequate ensembles and the need for detailed three-dimensional, three-component data. The next step in this program will be to explore the control of unsteady turbulent boundary layers with articulated vortex generators. Since this will be closely related to work in air by Prof. Eaton and his students (see Section 3 above), which is likely to develop much faster, we are considering delaying this next phase for the moment in order to initiate a new line of research in turbulent boundary layer control for which this facility is uniquely well suited. This proposed new work is described below.

5.3 Plans for Year Three and Beyond

Computational experiments of Moin and Kim have shown that properly-phased blowing and suction at the wall can inhibit wall turbulence. Specifically, they showed that by blowing (or sucking) at each wall mesh node with a wall-normal velocity v_w opposite to that detected at a mesh node at $y^+ = 10$ at every point on the surface of a channel, the mean skin friction in the channel could be reduced by approximately 20%.

Encouraged by this computation, we propose to redirect this subtask to the exploration of the potential of feedback-controlled localized blowing and suction for control of turbulent boundary layers. The initial work will focus on attempts to control turbulent spots in an unsteady laminar boundary layer. Subsequent studies will explore the control of separation in unsteady turbulent boundary layers. The proposed experimental program will be carried out in parallel with numerical simulations to be conducted at the NASA/Ames Research

Center under the aegis of the Center for Turbulence Research. The long-term objective is to develop a practical method for active control of turbulent boundary layers.

The new experiments will take good advantage of the unique capabilities of this facility. The transition spot experiments will be conducted at 0.3 m/sec on a flat plate at a point approximately 1 m from the leading edge, where the Reynolds number $Ux/\nu = 300,000$. Under these conditions the boundary layer thickness is approximately 1 cm, the T-S wavelength approximately 8 cm, the disturbance frequencies of the order of 10 Hz, and the transverse scale of three-dimensional disturbance structure of the order of 1 cm.

A porous bump will be placed on the control wall opposite the test region. The shape of this bump will be such that the free-stream velocity is uniform along the test surface with a finite bleed flow through the bump. Then, by reducing this bleed, a local free-stream acceleration can be imposed on the test boundary layer. This will enable us to impose either a favorable or adverse transient pressure gradient on the test boundary layer, a capability that will be important in the planned sensor-actuator development, as noted below.

In order to control the boundary layer we will need a sensor/actuator capable of sensing the near-wall velocity field and applying a controlled blowing or suction that depends on the strength and direction of the velocity normal to the wall in the near-wall region. The basic sensor/actuator concept is shown in Figure 5.3. Two thin film heater gauges of the type often used for skin friction measurement will be positioned just upstream of the suction/blowing slot. These gauges are sensitive to the local gradient in streamwise velocity at the wall, and hence (by continuity) their difference provides a measure of the normal velocity in the near-wall region.

The sensor/actuator development will take place in two steps. The first step will be to confirm the basic concept on an easily-built but rather large, easily-fabricated two-dimensional actuator, which will be operated in an unsteady two-dimensional laminar flow. The blowing/suction flow will be forced using a computer-controlled piston-cylinder system. Different slot angles will be investigated, as it seems likely that control will be more effective with some downstream component of injection. This first sensor/actuator will be tested using the two-dimensional transient capabilities described above. A variety of transient conditions will be imposed, and we shall attempt to provide compensating suction or blowing to reduce the effect of the imposed transient on the near-wall region of the test surface. The goal will be to determine the sensing arrangement, slot configuration, and control algorithm that are best suited for near-wall control.

In the second step of sensor/actuator development we will apply what was learned from the first step in the development of a miniature local actuator. Using standard shop practices it will be possible to construct sensor/actuators 1 cm or less in diameter, which is what will be required for the three-dimensional control experiments. Using micromanufacturing technology available in the Stanford Center for Integrated Systems (CIS) it might be possible to build a much smaller array of actuators in silicon. Prof. Reynolds is a participant in the CIS and his students have used these facilities in the past to fabricate two special sensors. This is an option that we will explore in due course.

This redirection of our work on boundary layer control will be carried out by a new student working under the direction of Prof. Reynolds, in consultation with Prof. Powell.

5.4 Participants

Faculty

Prof. W.C. Reynolds (fluid mechanics)

Prof. J.D. Powell (controls consultant)

Graduate Research Assistants

Major William Humphreys (flow experiments, Ph.D. Dec 1988)

Mr. Andrew Carlson (facility electronics, Ph.D 1989)

Mr. Roy Henk (facility mechanical, Ph.D. 1989)

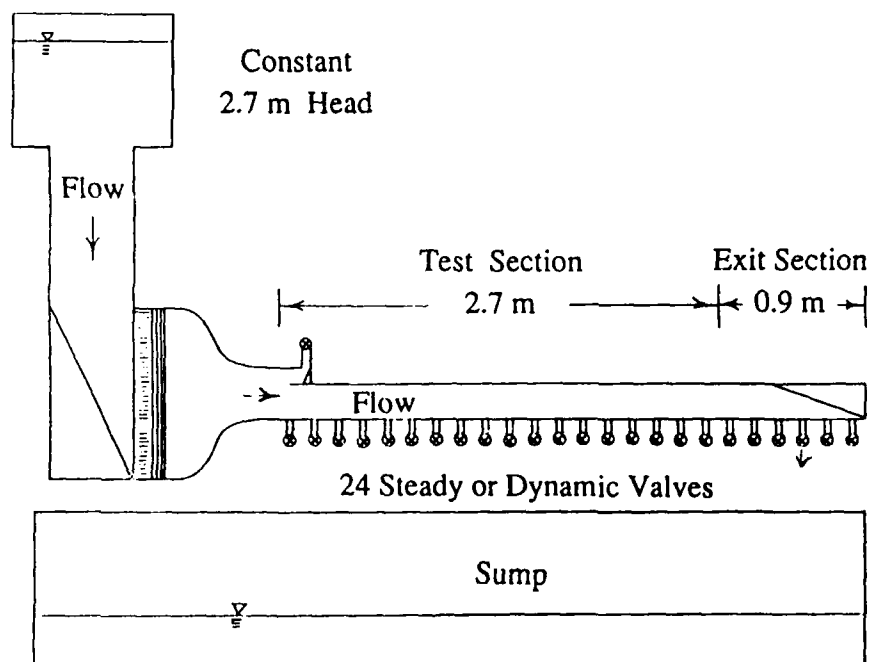


Figure 5.1 Schematic of the Unsteady Flow Facility.

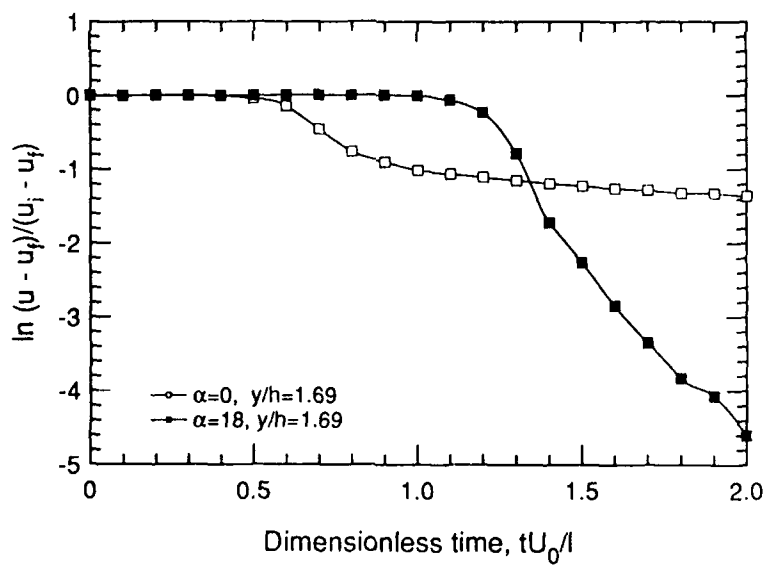
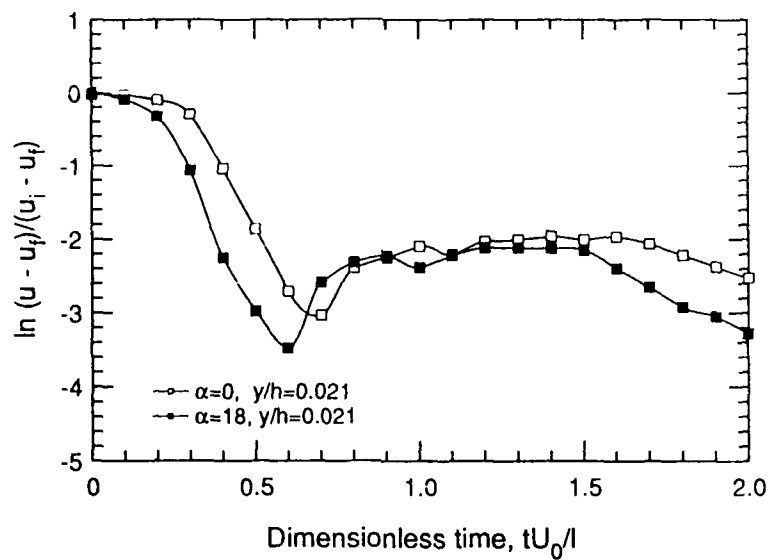


Figure 5.2 Flow response to suddenly imposed adverse pressure gradient. a) Near-wall region. b) Outer region.

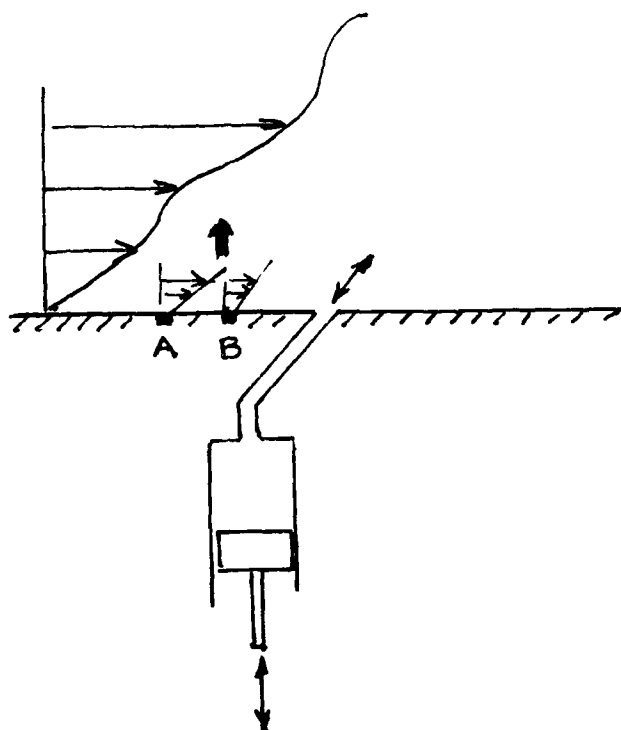


Figure 5.3 Sensor-actuator concept for proposed new experiments.

6. HOLOGRAPHICAL VORTICITY MEASUREMENT

6.1 Background and Objectives

Vorticity is a fundamental property of fluid flows that, at present, cannot be accurately measured with high spatial and temporal resolution. Previous attempts to measure vorticity can be classified into three groups:

1. the vorticity is derived from multiple measurements of the velocity;
2. the vorticity is inferred from the stress that the associated velocity gradients apply on solid boundaries in the fluid; and
3. vorticity is related to the deformation of grid patterns written in the flow.

In the past, the vorticity, defined as:

$$\omega_i = \epsilon_{ijk} \frac{\partial u_j}{\partial x_k}$$

has been computed from the estimates of the gradients involved. These approaches, however, have met with varying degrees of success, because of the following difficulties:

- The need for several spatially resolved measuring points in the first group of techniques results in a marked loss in spatial resolution; estimating the gradients is prone to large errors, since two nearly equal quantities must be subtracted; when using LDV based techniques there is no guarantee of the simultaneity of the measurements at different locations, due to the intrinsically random nature of the method.
- The addition of macroscopic particles for measuring the rate of rotation of solid spheres imbedded with a small mirror is always undesirable, since it may affect the flow dynamics; without such addition, the second group of techniques are restricted to measurements at the flow boundaries only; furthermore, it is questionable that the rotation of particles follows that of the fluid, specially at the high temporal frequencies associated with the small scales of turbulent flows.
- In the grid based methods, the spatial resolution is limited and accuracy is sacrificed, because this technique relies on measuring the relative displacement of the nodes of a grid which, again, requires the subtraction of nearly equal quantities.

Considering the methods currently used for obtaining vorticity, it is evident that none of them provides the combination of spatial and temporal resolution required for producing reliable measurements of the vorticity distribution at the small scales of turbulence. It is the objective of this research to provide such measurements.

The method developed by us during the past two years allows the measurement of the velocity gradients in a fluid flow by detecting the rotation of holographic markers—holograms—written in fluids sensitized with photochromic dyes. The new orientation of the hologram is analyzed by measuring its optical diffraction pattern. The spatial and temporal resolution obtainable with this method are well suited for the measurement of the

small scales in turbulent flows. In particular, highly accurate measurements in turbulent boundary layers very close to the wall may be made. The principal innovations are the usage of photochromic materials as the recording medium and of volume holograms, as compared to thin holograms, as the fluid based marker. We also provide a complete analysis of the fluidic-optical processes involved, which rigorously establishes the basis of the experimental method. With this approach, measuring volumes as small as $95\text{ }\mu\text{m}$ and a resolution of the gradient values of 3 s^{-1} are obtained.

The usage of photochromic materials as the sensitizing agent provides for a high spatial resolution and for a large range of vorticity, since the diffusion, which is the mechanism that limits the life of the holograms, is two orders of magnitude smaller for photochromic based holograms than for thermal gratings used previously. The usage of volumetric cross-beam holograms and their associated Bragg diffraction mechanism allows a whole new variety of experimental arrangements to be implemented for the measurement of several of the components of the velocity gradient tensor. Among them, we demonstrate an arrangement for measuring a single velocity gradient with simple optical accessibility requirements. We also propose an experimental arrangement capable of measuring true vorticity by the simultaneous measurement of two cross-terms of the velocity gradient tensor.

6.2 Progress to Date

In general, the study of cross-beam holograms in a deformable medium can be separated into three distinct phases: writing, deformation and readout. Assuming that no appreciable movement of the medium takes place during the writing process, the resulting hologram will depend only on the characteristics of the writing beams and on the type of writing mechanism employed. Thermal absorption, photochromism and photoinduced chemical reactions are possible mechanisms for writing holograms. The second process deals with the effect of the deformation of the supporting medium on the hologram. Simultaneously, other intrinsic effects may be acting on the hologram, such as diffusion, molecular relaxation or back chemical reaction, all of which, by themselves, tend to lower the diffracting capability of the hologram by modifying the hologram shape, intensity and modulation as a function of time. Finally, in the third process the hologram is being read out to infer its new state. Optimal readout will not, in general, be a simple task, since the shape, orientation, and intensity of the hologram are unknown because of the random nature of various perturbations.

In this research we are concerned with all three of the processes described above, though we place a major emphasis on the second and the third one, namely the convective-diffusive evolution and the optical readout. The first process, dealing with the writing of such diffraction gratings, has been considered in the literature for the case of thermal gratings. Although the usage of photochromic dyes as holographic recording materials has been suggested earlier, the diffraction properties of deformed holograms resulting from fluid motion have not been studied before. We provide a detailed study of these materials from the point of view of their applicability to experimental fluid mechanics and, more

specifically, on their use as fluid holographic recording materials. We have applied the new technique to the measurement of velocity gradients in a thin boundary layer with high spatial resolution ($\leq 95\mu\text{m}$) and an extended range of gradients from $3 - 300\text{s}^{-1}$.

6.2.1 Experimental results

An extensive report of the experimental activities is contained in the doctoral thesis of Juan C. Agüí and four publications listed below. The most relevant points are:

- High resolution gradient measurements using volume holograms of $95\mu\text{m}$ in cross section have been made in a turbulent boundary layer, including measurements very close to the wall.
- Measurement of moderately high Reynolds number ($\text{Re}=1500$ and $\text{Re}=2000$) channel flows have been successfully measured.
- An experimental arrangement for the measurement of the full component of the vorticity along the optical axis has been invented.
- A patent has been applied for, covering the unique aspects of this method, such as the usage of volume holograms, liquid photochromic materials for the writing of the holograms, and the extension to other gradients and to full vorticity measurements.

6.2.2. Theoretical activities

Two articles have been recently published (August '88) in the Journal of the Optical Society of America-A which contain full details of the analytical modelling of the effect of fluid flow on volume holograms, and of the diffracting capabilities of such strained holograms.

The process of writing such holograms in fluids, using photochromic materials and the most relevant experimental results are being compiled into an article to be submitted shortly.

6.2.3 Discussion of recent results

The major accomplishments of our research may be summarized as follows:

- Evaluation and selection of a large number of photochromic fluids for use in vorticity measurements.
- Design and implementation of a new optical technique for measuring velocity gradients and vorticity.
- A full theoretical analysis of the fundamental processes involved in making holographic strain measurements in fluids using volume holograms.

- Measurement of strain in a turbulent channel flow at moderate to high Reynolds numbers (1500, 2000), including measurements very close to the wall ($< 95\mu m$) and over an extended range of strain values from $3-300 s^{-1}$.

An example of a velocity gradient profile is displayed in Fig. 6.1. The spatial resolution of the measurement is approximately $95\mu m$, with the measurement point closest to the wall being $95\mu m$ from it. Figure 6.1 also contains an estimate of the fluctuations of the measured velocity gradient.

The major benefits of our new technique over previous methods are:

- *Spatial resolution.* The holographic measurements are *single point* measurements of a gradient, and do not require the measurement of velocity at two distinct points. As a result the spatial resolution is very high ($< 95\mu m$).
- *Temporal resolution.* The method is applicable to steady and nonsteady flows as well. The flow rotation sets the time scale of the measurement. The only limit is set by the diffusion, which restricts the lifetime of the hologram and the minimum value of the measurable gradient.
- *Accuracy.* The velocity gradients are derived from the angular evolution of the diffracted spot. A number of scans of the diffracted spot are acquired for each measurement and each of them provides a position of the center of gravity of the diffracted spot. The moving angular position of the center of gravity is then used for the estimation of the velocity gradient. Since the data reduction scheme relies on a number of data points, the accuracy of the gradient measurement is higher than when only one diffracted spot is measured. A 3-fold increase in accuracy is typically obtained when using ten estimates of the gradient at each point. It should be noted here, that these estimates are all obtained during the same run within the time resolution of the gradient measurement for the ranges of $3-300 s^{-1}$.
- *Lagrangian versus Eulerian approaches.* Since the small hologram is convected with the local velocity, the analysis of the rotation of the hologram results in a Lagrangian, rather than an Eulerian, measurement of the velocity gradient. The distance traveled by the marker during the time needed to detect the speed of its rotation can be seen to be similar to the volume of material sweeping by the measuring point during the required observation time, in an Eulerian measurement. For the Lagrangian measurements, however, the frozen-flow Taylor hypothesis does not need to be assumed.

6.3 Plans for Year Three and Beyond

Our results to date have generated considerable interest in the research community. In particular, Prof. Reynolds would like to use the technique for making vorticity measurements in the unsteady water channel facility (Section 5). To make this feasible, it is necessary to use a different photochromic dye than we have used in our small facility (TSNBPI). The present dye has to be dissolved in an organic fluid (Dioxene at very small

concentrations) and water. The solvent is difficult to handle safely in the large quantities required for a full scale water tunnel experiment.

As a short-term goal we wish to study several other photochromic dyes that can be used for our purpose and are soluble in a less hazardous solvent. We have identified several such candidates, and need to evaluate their properties and choose the optimum dye in terms of photochromic response and the solvent needed. In the longer term, beyond year three we wish to implement the new technique in Prof. Reynolds facility.

We propose to carry out the following research during the third year of the research effort with the aim to find a photochromic dye suitable for use in large water facilities:

- Investigate water-based, drain-disposable photochromic materials for use in our new vorticity measurement technique. It is desirable to use only water as the solvent, and still use visible lasers for the writing and reading of the holograms. Further investigations of the photochromic characteristics of Malachite Green solutions may produce a material with all the required properties.

As a longer term goal, for the end of year three and beyond, we propose an:

- Investigation of techniques for measuring alternate gradients and full vorticity. We have invented a whole variety of alternate experimental arrangements capable of measuring different components of the velocity gradient tensor and the full components of the vorticity. Of prime interest are the measurements of vorticity, using a two-channel arrangement of the our present configuration, and the measurement of downstream vorticity in boundary layers.

6.4 Participants

The participants in this research are:

Principal Investigator: Prof. Lambertus Hesselink

Graduate Research Assistant: Juan C. Agüí , Ph.D. September 1988

6.5 Publications to Date

AGÜÍ , J.C. and L. HESSELINK, *Holographic measurements of velocity gradients in fluids*, Am. Phys. Soc. Bulletin, 1987 .

AGÜÍ , J.C. and L. HESSELINK, *The usage of photochromic materials and their applications to experimental fluid mechanics*, submitted to Phys Fluids.

AGÜÍ , J.C. and L. HESSELINK, *Holograms in motion. i: the effect of fluid motion on volume holograms*, J. Opt. Soc. Am. A, V. 5, No. 8, pp 1287-1296, 1988.

AGÜÍ , J.C. and L. HESSELINK, *Holograms in motion. ii: the diffracting capabilities of strained holograms*, J. Opt. Soc. Am. A, V. 5, No. 8, pp 1297-1308, 1988.

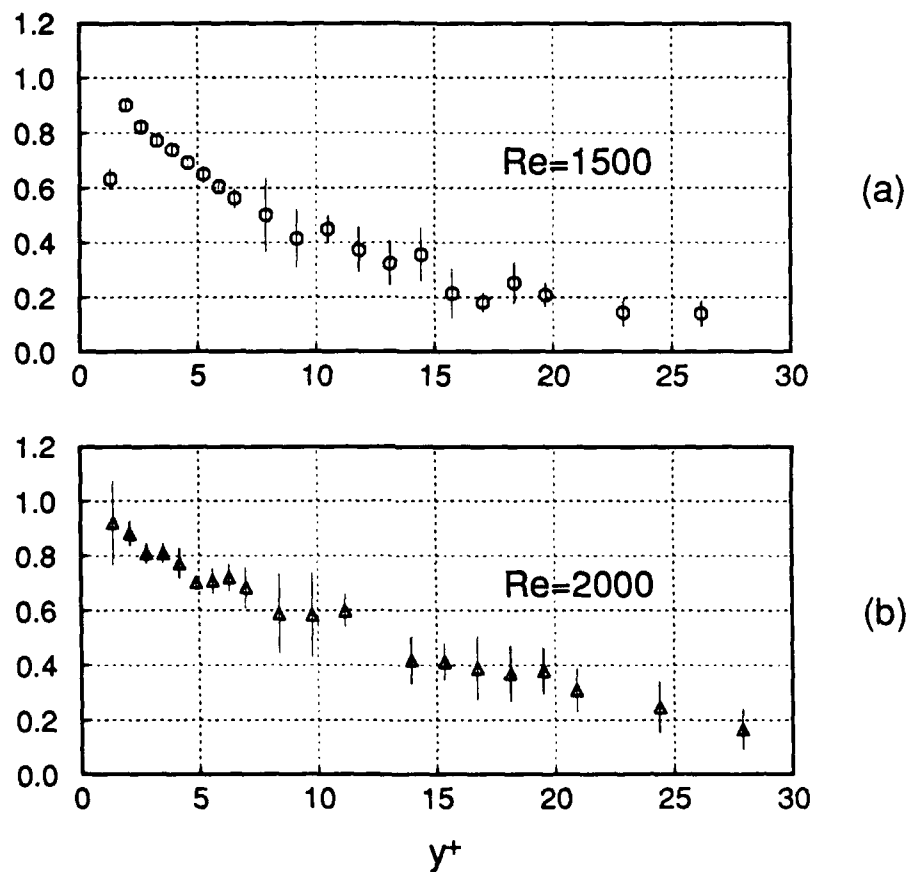


Figure 6.1 Nondimensional gradient profile $((\partial u / \partial y) / (\partial u / \partial y)_{y=0})$ versus distance to the wall ($y^+ = yu^* / \nu$) across the lower boundary layer in a rectangular channel. Vertical segments show the estimated variability of the gradient at the corresponding station. Reynolds numbers based on the flux velocity and the channel equivalent diameter are: (a) 1500, (b) 2000.

7. VORTEX CONTROL FOR DELTA WINGS THROUGH LEADING EDGE BLOWING

7.1 Background and Objectives

The flow over a delta wing at high angle of attack is determined by vortex shedding and subsequent breakdown. This may occur in an asymmetric and sometimes random way, leading to loss of aircraft stability or control. The goal of the present program is to understand the mechanisms involved in leading edge vortical flow separation and bursting, and to use this understanding to develop an effective means for active flow control of the flow which will provide the forces and moments necessary to maintain aircraft stability.

With a sharp leading edge the separation point is fixed by the geometry and hence difficult to modify. However, with a blunt leading edge relatively small amounts of tangential blowing (via a leading edge wall jet) can be used to make major modifications in the vortical flow field over the wing. Thus, this program has concentrated on leading edge blowing as the means of flow control.

The overall objective is to improve the understanding of steady and unsteady vortex flows associated with delta wings and to carry out experimental and theoretical demonstrations of the ability to actively control these flows using leading edge blowing. The specific objectives are:

1. develop a basic understanding of the processes by which separation regulates the steady and unsteady vortex flow over a delta wing;
2. obtain basic data on these flows needed for control system design using advanced 3-d flow visualization and sensors mounted on the wing;
3. examine the special problems of feedback control of delta wing vortex flows and implement an active control system in both a computer simulation and a wind tunnel model;
4. utilize the foregoing information in a dynamic simulation of an advanced aircraft in typical supermaneuvers.

7.2 Progress to Date

At the start of this project, a preliminary investigation of the action of the leading edge wall jet on a vortex had been undertaken using a half-span delta wing in the Stanford low speed wind tunnel. This model was instrumented for steady pressure measurements and was used to demonstrate the strong effects of wall jet blowing momentum on the external flow field and the distribution of pressure on the wing.

Since that time significant progress has been made in (1) the understanding of steady and unsteady aerodynamic phenomena, (2) implementing the flow control mechanisms for a delta wing and (3) modelling the influence of this control on the aircraft dynamics at high angle of attack conditions.

During the past two years of the current program, the action of the leading edge wall jet in displacing the point of flow separation on the wing upper surface, its influence on vortex strength and location, and its ability to restore a burst vortex to an orderly condition, have been well established.

The sensing of the flow conditions from surface pressure measurements complemented by advanced flow visualization and the use of this information to provide active control of the wall jet blowing momentum have been demonstrated in a preliminary way; and the incorporation of aerodynamic/dynamic interaction effects on aircraft forces and moments have been modelled in a computer simulation.

7.2.1 First Year Progress

During the first year of the present work (September 1986 - September 1987) a more comprehensive effort was made to understand the effects of leading edge blowing and to extend this understanding to the unsteady response of the flow over the wing and in the wake. The progress that was made during the first year has been reported previously and is summarized briefly as follows:

- a. The low speed wind tunnel in the Aeronautics/Astronautics Department was repaired, upgraded, and calibrated in preparation for the investigation of unsteady blowing effects.
- b. The laboratory was significantly improved by the installation of a copper vapor laser for flow visualization studies and a new data acquisition system based on an IBM PC-AT placed in service, providing sampling at up to 130 kHz on sixteen single-ended A/D channels.
- c. New software was developed for display of a stack of unevenly-spaced cross sections of the flow obtained by rapidly scanning a sheet of laser light through the smoke-laden fluid. A smooth-surface representation of the vortical structures may be displayed in stereo, allowing detailed topological studies of the complex flow field to be made. Interactive surface peeling allows interior detail to be examined. This information is of importance for designing the optimum location and number of sensing elements on the surface of the wing.
- d. An unsteady blowing system with fast response (5 msec) was constructed and placed in operation. The dramatic response of the external flow to adjustments in blowing rate was demonstrated and presented at the AFOSR Workshop in July 1987.
- e. A new wind tunnel half-span model was designed and fabricated. The model is suitable for transient flow experiments, having the following features: constant radius leading edge with variable slot height capability, sharp trailing edge, unsteady pressure instrumentation, trailing edge flap. On this model open-loop flow control through modulation of blowing was demonstrated.
- f. Theoretical work on a mathematical model for the unsteady aerodynamics with leading edge blowing was initiated to represent the unburst flow (pre-stall) case, and a

steady Navier-Stokes numerical solution for the symmetric flow was initiated to provide a full numerical simulation of the flow in both the unburst (pre-stall) and burst (post-stall) conditions.

7.2.2 Second Year Progress

During the second year (September 1987-September 1988) very significant progress was made toward all of the program objectives as summarized below. This progress places the program in a strong position to obtain comprehensive results, both experimentally and theoretically, during the third year of the contract (September 1988 - September 1989).

The symmetric steady flow (*i.e.* half-span delta wing) was fully investigated in the wind tunnel to establish the steady-state end conditions for the transient flow. It was demonstrated that orderly vortex flow could be established at angles of attack up to 60° . In particular a detailed understanding of the mechanism by which this flow is controlled was determined:

- a. For sufficiently low angles of attack the vortex is unburst and produces suction on the upper surface of the wing, providing the so-called vortical lift contribution. Leading edge blowing delays separation of the vortex sheet from the upper surface (*i.e.*, moves the separation inboard), weakening the vortex and causing a reduction in vortex lift; however, the blowing permits the flow to accelerate around the leading edge, thereby increasing the attached flow contribution to the lift (*i.e.* leading edge suction lift). The net result is a significant redistribution of pressure on the wing (moving the lift outboard) with little change in overall lift but with a large change in rolling moment.
- b. At high angles of attack, in the absence of blowing, the vortex bursts, causing a loss of orderly flow over the wing (completely stalled flow). When blowing is present, however, the additional momentum introduced by the wall jet is entrained into the vortex causing an acceleration of the flow in the vortex core; thus, the vortex remains unburst and orderly flow over the wing is reestablished. The net result is an increase in overall lift and an increase in rolling moment.

This interpretation of the wind tunnel results was fully verified by conducting Navier-Stokes computations of the wind tunnel model configuration with the same angle of attack and blowing momentum conditions. Detailed surface pressure distributions were compared and found to be in very good agreement with experiment (see Fig. 7.1). Moreover, the Navier-Stokes computations revealed details of the flow inside the vortex core; in particular they confirmed the presence of vortex bursting without blowing and the reestablishment of an unburst vortex with blowing.

The Navier-Stokes computation also suggested that the influence of blowing on the vortex would also be felt near the wing trailing edge. A series of experiments was undertaken in the wind tunnel to confirm that the effectiveness of trailing edge flaps could be restored through leading edge blowing. This was indeed verified and it was demonstrated that over a range of angle of attack where the flow over the flaps is normally stalled, trailing edge flap effectiveness was completely restored with modest levels of blowing.

Once we had obtained this information on the steady-state configuration of the flow, with and without blowing, and including vortex bursting, the effort was then devoted exclusively to the transient blowing case. The primary questions to be answered by the wind tunnel experiments using the half-span model concerned the time scales required for the external flow over the wing and in the wake to respond to the onset of blowing or to changes in the magnitude of the blowing momentum (see Fig. 7.2). Two cases were considered: (1) transition from an unburst vortex to a new unburst vortex; and (2) transition from a burst vortex to an unburst vortex. At high angles of attack the second case is of extreme interest since this will establish the time scale required for a stalled wing to become unstalled when blowing is applied to the leading edge.

These transient flow experiments are now essentially complete and are being analyzed in detail. Preliminary results show that two distinct time scales are involved (in addition to the small internal flow time lag). The time lag associated with unburst flow was found to be relatively short in terms of the dimensionless parameter, $\frac{\text{time} \times \text{free stream velocity}}{\text{chord}} = \frac{TU_{\infty}}{C}$. Values of $\frac{TU_{\infty}}{C} \approx \frac{1}{2}$ were measured, indicating that the flow was able to adjust in the time taken for the wing to travel a distance equal to half a chord. On the other hand, the "burst to unburst" time lag was appreciably larger, $\frac{TU_{\infty}}{C} \approx 10$, indicating the flow required an adjustment time of $10\frac{C}{U_{\infty}}$ to establish an orderly unburst vortex flow from an originally burst vortex (i.e. to unstall the wing). These results are now being documented over large ranges of angle of attack and blowing rate to provide an experimental data base for the definition of control laws. These active control algorithms will be developed in the third year of the program.

The half-span wind tunnel model has been the primary tool for exploring the fundamental time lags in the flow that are important to the formulation of control laws and the modelling of control systems. However, such a half-span model necessarily restricts the investigation to symmetric flows, while many of the most promising applications of this approach are associated with aircraft lateral control. In order to overcome this restriction, the design and fabrication of a full-span model was undertaken for use in the Stanford low speed tunnel. This model is now complete and initial tests have been conducted. The model permits investigation of the degree of cross-coupling between leading edge blowing and the behavior of the vortex on the opposite wing. It is capable of angles of attack up to 60° , yaw of 10° and roll of 30° , with independently controlled blowing from each leading edge. Thus, asymmetries in the flow imposed by blowing (to create control moments) or asymmetries corrected by blowing (e.g. correction of asymmetric vortex bursting) can be examined. The capability to produce roll control for periodic roll motion has been included in the model design to investigate unsteady control tasks for the proposed control systems.

In conjunction with the local point measurements, a closely coupled effort of advanced 3-D flow visualization has been undertaken. The 3-D flow visualization allows global measurement of the flow topology. This information is of particular importance when considering the optimum location and number of sensors needed on the surface of the wing to monitor the overall flow topology. We have made a video movie showing preliminary

results of leading edge blowing on the global flow structure. Progress made in this area to date includes:

- a. development and implementation of a new smoke generator for use with high speed movie recording. The smoke generator allows smoke to be injected either into the wing boundary layer to visualize the roll up of the vortex sheet or into the free stream for visualization of the vortex core (see Fig. 7.2c).
- b. An advanced laser scanning system in conjunction with a copper vapor laser and a high speed rotating drum camera has been designed and implemented. Preliminary results have been obtained.
- c. Sophisticated new software has been developed for display and evaluation of the stack of two-dimensional cross sections. Under cursor control and in stereo the interface between smoke laden and clear fluid may be displayed and obscuring outer layers of the rolled up vortex may be interactively peeled away to study interior structures.

This effort of global flow visualization has strongly interacted with the experimental effort to document the flow structure using surface pressure measurements.

Closely coupled with this experimental investigation is the development and application of an integrated unsteady aerodynamics/vehicle dynamics simulation code. The program is used to predict the nonlinear unsteady aerodynamics of a delta wing in the pre-stall flight regime. This code, described in a previous progress report, is now essentially complete. It is based on a low order panel representation of the wing, combined with time accurate vortex tracking and a model of leading edge blowing effects (see Fig. 7.3). It has been applied to both symmetric and asymmetric cases, with and without blowing. It has served to verify the experimental results on aerodynamic lags and extend the low angle of attack results to asymmetric flight conditions.

Progress during this second year includes:

- a. The extension of the code to permit asymmetric flow conditions including rolling motion, sideslip, and asymmetric blowing (results illustrate the interaction between blowing and vortices on the other side of the wing).
- b. Unsteady blowing results - these results confirm the presence of two time scales associated respectively with local adjustment of the flow over the wing (short lag) and adjustment of the trailing wake (long lag).
- c. Refinement of the blowing model using experimental results to provide the relationship between blowing momentum and shed vortex strength.
- d. Investigation of thickness effects by the application of source panels and second order corrections due to Regels and Walker.
- e. Application to unsteady motion, with results for prescribed pitching and plunging motion of a delta wing.

Recently, the program has been integrated with a nonlinear dynamics simulation routine and used to predict the single degree-of-freedom wing rock phenomenon (Fig. 7.4). Results agree very well with experimental data in the unblown case. Work is underway to investigate the open-loop and closed-loop response of the wing with blowing.

The development of this prediction code has interacted strongly with the experimental effort and the Navier-Stokes computational effort and should provide a basis for the forthcoming attempts to model the post-stall case and more complex vehicle dynamic simulations.

The effort on active controls will be undertaken primarily in the third year of the contract; however in preparation for this effort an unsteady blowing control system has been designed, fabricated and tested to verify the required linearity of blowing momentum to plenum pressure. Pressure-sensing electronics have been installed in the plenum and on the half-span model to provide feedback information. The central component of this system is a high bandwidth plenum pressure control valve capable of maintaining or setting a desired plenum pressure as a function of input external conditions (angle of attack *etc.*). Fabrication is complete and extensive testing is now underway. Numerical simulations of the design suggest that adequate control valve deflection will be achieved in approximately 10 msec and should be quite acceptable for the tunnel conditions. This control system, when applied to the full span model, in 1989, should permit extended roll maneuvers to be simulated in the Stanford wind tunnel.

7.3 Plans for Year 3 and Beyond

The third year effort for this contract will benefit from the progress and preparation made in the previous two-year period: the availability of a full-span wind tunnel model with independent leading-edge blowing control systems; availability of a sophisticated 3-D flow visualization system and novel display and analysis software; the identification of the flow lag-times necessary to define the control system algorithms; a Navier-Stokes code that has successfully computed vortex behavior including bursting (and which can be extended to asymmetric and unsteady flow conditions); and a computer model of the wing dynamics including the improved effectiveness of its aerodynamic control due to blowing.

The third year program described below has the following primary purposes:

1. to demonstrate that active control of the wing aerodynamics can be achieved, through leading edge blowing, at angles of attack and yaw at which the wing is otherwise fully stalled.
2. to demonstrate that Navier-Stokes computation can represent these conditions with sufficient accuracy to predict asymmetric and unsteady forces and moments.
3. to formulate control strategies and implement them through appropriate software and hardware, in the wind tunnel test program.
4. to combine the aerodynamic, flow visualization and control system results in a computer model of the aircraft dynamic response, capable of predicting the motion of the partially-restrained and unrestrained vehicle in complex dynamic maneuvers, including supermaneuvers.

To achieve these purposes the following tasks will be completed:

- The steady state aerodynamics of the half-span delta wing throughout the angle of attack range $0 - 60^\circ$ (at zero yaw) with leading edge blowing will be fully documented using local point measurements and global 3-D flow visualization.
- The transient aerodynamics of the half-span delta wing showing the unsteady response of the vortical flow to changes in blowing momentum will be fully investigated and documented.
- The lag times, for both the burst and unburst vortex cases, will be identified as a function of angle of attack and blowing momentum.
- This information will be incorporated into a blowing control system capable of controlling the half span wing aerodynamics in the pre-stall and post-stall condition (symmetric flow).
- The steady state and unsteady aerodynamics of the full span wing with blowing will be investigated over a full range of angle-of-attack ($0 - 60^\circ$) with and without yaw.
- The time lags associated with cross-flow aerodynamics will be determined (i.e. the influence of blowing on opposite wing pressure distribution).
- This information will be used to formulate control algorithms for the coupled leading edge blowing systems to permit roll control at angle of attack and yaw.
- The Navier-Stokes code will be modified to provide computation of asymmetric and unsteady flows for the full span wing under conditions representative of those tested in the wind tunnel.
- The full span model (which is instrumented for unsteady pressure, and force and moment balance measurements) will be used in conjunction with the control system to demonstrate active control of the wing in roll throughout the angle of attack and yaw range.
- The results of the foregoing tasks will be used to investigate partially restrained and unrestrained motions at high angles of attack with active blowing control.
- The dynamics simulation program will be used to investigate the open-loop and closed-loop response of an aircraft with the blowing control system in several flight conditions, identifying situations in which the control system may be used to best advantage.

The research results anticipated from this third-year program will provide the essential groundwork for a more comprehensive effort to bring this technology into the mainstream of future maneuvering aircraft design. Future efforts beyond 1989 should seek to investigate the possibility of aircraft maneuvers at arbitrarily large angles of attack and yaw through the use of fuselage/strake blowing in combination with wing blowing (it is known that fuselage/strake-generated vortices interact strongly with the wing and tail aerodynamics especially at high angle of attack). Recent tests at NASA Ames of a Stanford-designed fuselage-blowing model at an angle of attack of 45° showed an extremely strong influence of blowing and generated large side forces on the fuselage. (This result also suggests that the concept has broad implications for unconventional configurations with reduced radar cross-section.)

While the details of the effort beyond 1989 have not been fully defined they are envisioned to include the following ingredients:

- An experimental program on an actively-controlled wind tunnel model of a generic maneuvering aircraft to investigate the effects of fuselage/strake blowing, in combination with a wing using leading edge blowing. Such a program would also investigate the application of the control scheme to unconventional designs.
- A complete Navier-Stokes analysis of this configuration with its active control system to fully understand the flow field control system interaction on a complete aircraft.
- The use of experimental results including advanced 3-D flow visualization, Navier-Stokes computations, and dynamic simulation codes to explore a variety of relevant control problems for maneuvering flight at very large angles of attack and yaw.

The results of the current three-year AFOSR contract have opened up a completely new approach to aircraft stability and control which may have a profound influence on the design of future aircraft and missiles, and on operational tactics. It is recognized that the scope of the effort suggested for 1990 and beyond will probably involve other DOD organizations in addition to AFOSR. It is recommended that AFOSR formulate a comprehensive approach, in conjunction with DARPA and WADC (Flight Dynamics Lab) to exploit the ideas that have been generated within the current AFOSR program.

7.4 Participants

Faculty co-principal investigators

Prof. L. Roberts (aerodynamics; overall coordination)
Prof. L. Hesselink (advanced 3-D flow visualization)
Prof. I. Kroo (aerodynamics, modelling and control)
Prof. J. D. Powell (control systems)

Research Associates

Norman J. Wood (fluid mechanics, instrumentation)
Domingo Tavella (Navier-Stokes computation)

Graduate Research Assistants

M. Yoda (Advanced 3-D flow visualization, Ph.D. 1990)
K. T. Lee (wind tunnel experiments, Ph.D. 1990)
Grant Wong (controls experiments, Ph.D. 1990)
Z. Mittelman (aircraft dynamics modelling, Ph.D. 1989)

Faculty Consultants

Prof. W. C. Reynolds (fluid mechanics)
Prof. Holt Ashley (aerodynamics, dynamics)
Prof. A. Bryson (control theory)

Professor Roberts provides overall coordination of this program, which is centered in the Department of Aeronautics and Astronautics.

7.5 Publications to Date

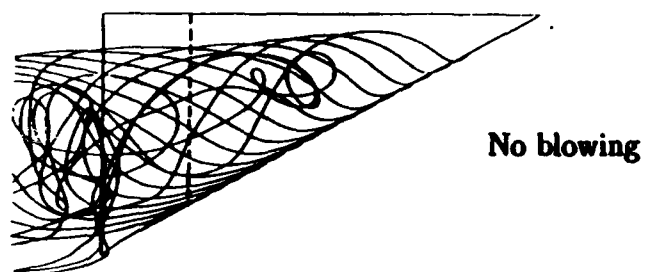
WOOD, N.J. and L. ROBERTS, *The Control of Vortical Lift on Delta Wings by Tangential Leading Edge Blowing*, AIAA paper 87-0158, 25th Aerospace Sciences Meeting, Reno Nevada, January 1987.

WOOD, N.J., L. ROBERTS, and K.T. Lee, *The Control of Vortical Flow on a Delta Wing at High Angles of Attack*, AIAA paper 87-2278, August 1987.

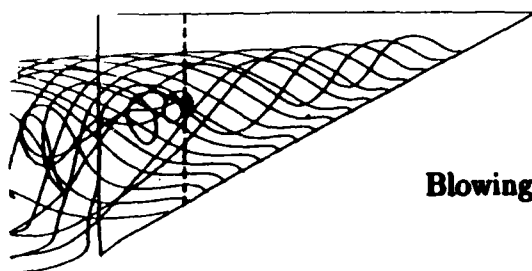
ROBERTS, L., L. HESSELINK, I. KROO, and N.J. WOOD, *The Control of Vortical Flows over a Delta Wing*, AFOSR Workshop on Unsteady Separated Flows, Colorado Springs, July 1987.

WOOD, N.J., K.T. LEE, and L. ROBERTS, *Dynamic Control of Vortical Flow on Delta Wings at High Angles of Attack*, Paper 88-4333 CP, AIAA Atmospheric Flight Mechanics Conference, Minneapolis, MN., August 1987.

PARTICLE TRACES - PLAN VIEW



No blowing



Blowing : $C_\mu = 0.038$

PRESSURE DISTRIBUTION.

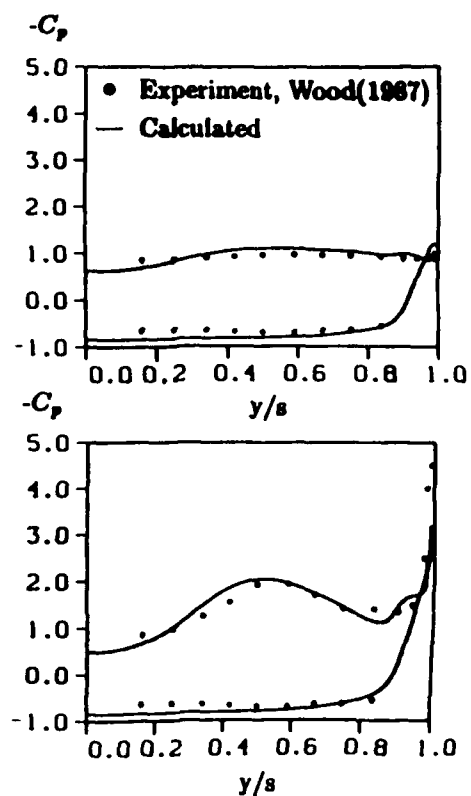


Figure 7.1 Vortex particle traces and pressure distributions, without and with blowing.

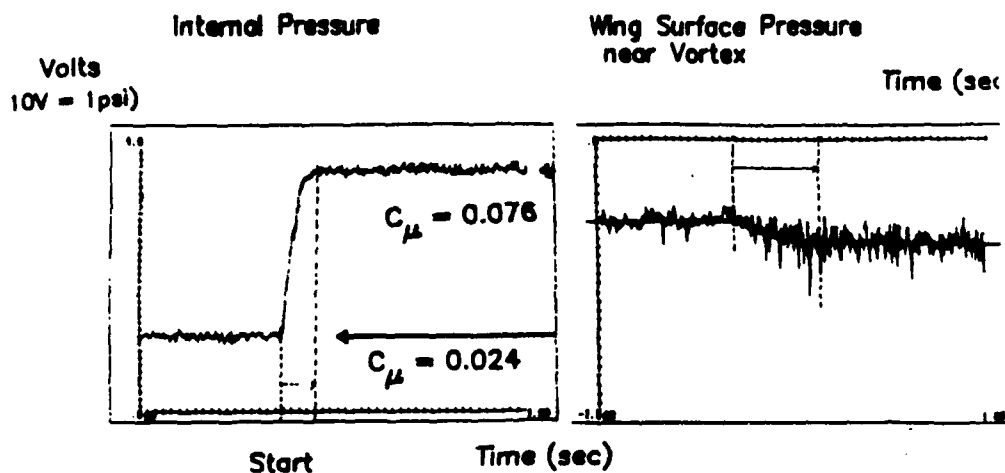


Figure 7.2a Time lag between internal blowing and external surface pressure (measured).

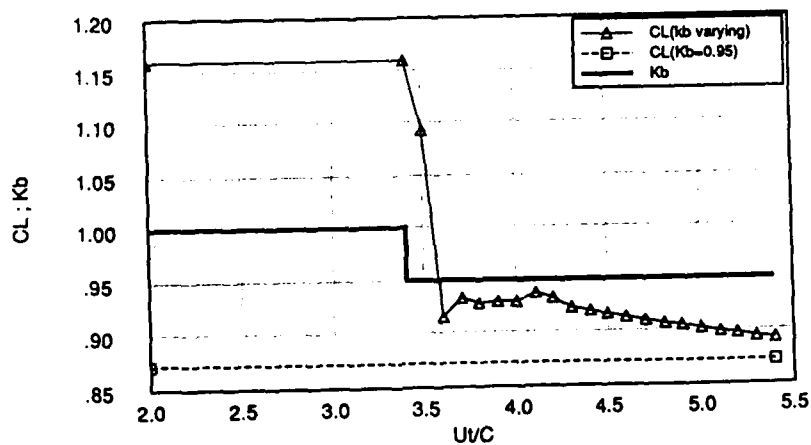


Figure 7.2b Time lag between lift coefficient and blowing (Kb) (computed).

Figure 7.2 Time response to unsteady blowing for $\alpha = 30^\circ$.

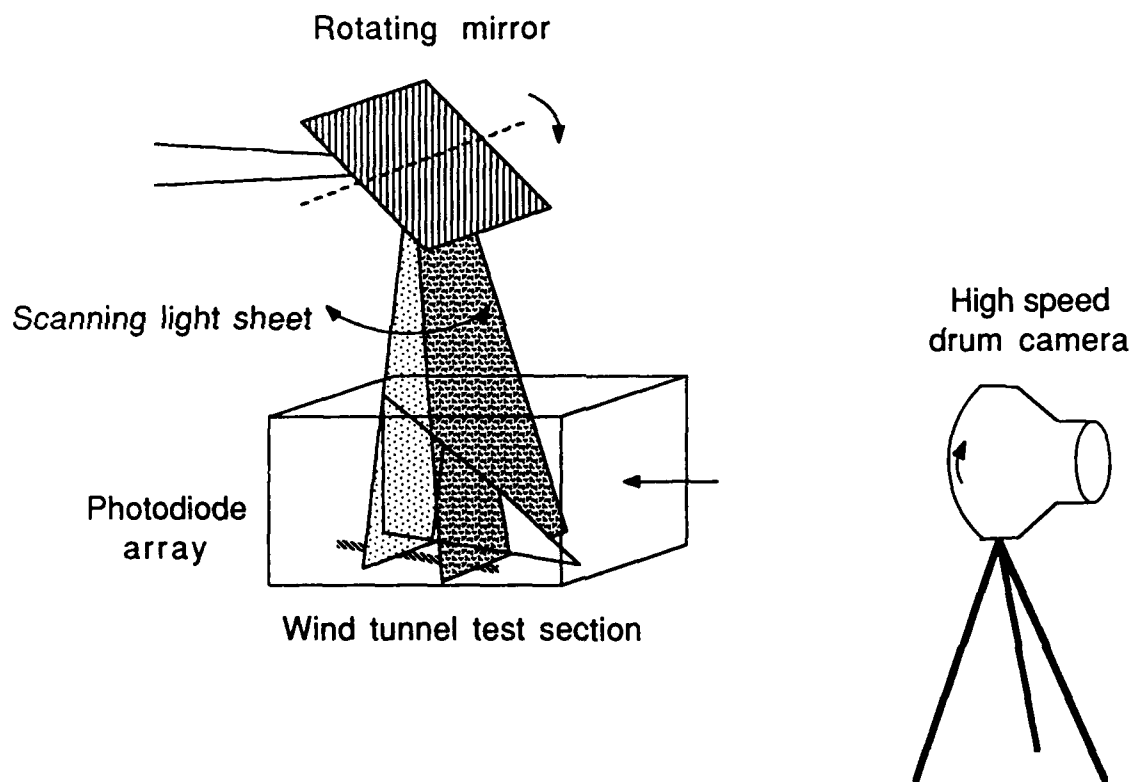


Figure 7.2c Recording system.

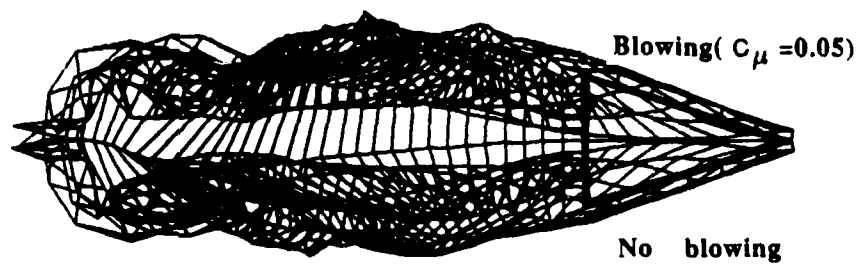


Figure 7.3 Unsteady panel calculation for asymmetric blowing on delta wing at zero yaw.

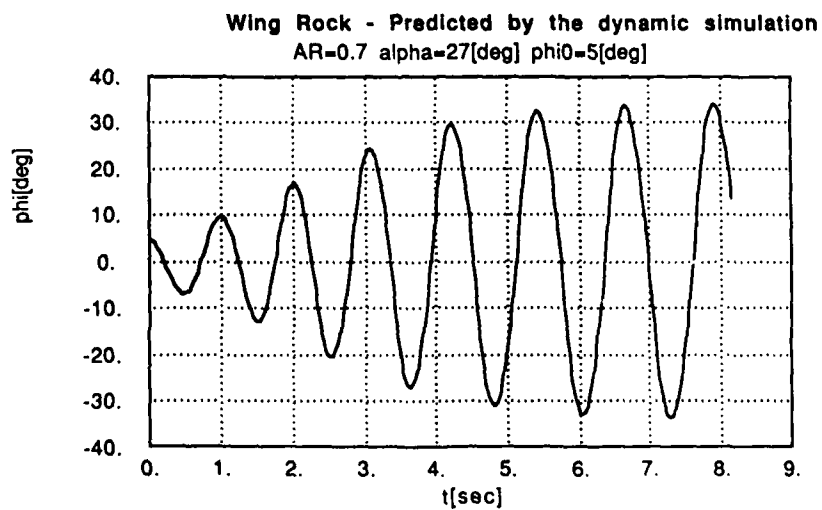


Figure 7.4 Wing rock predicted by the dynamic simulation.